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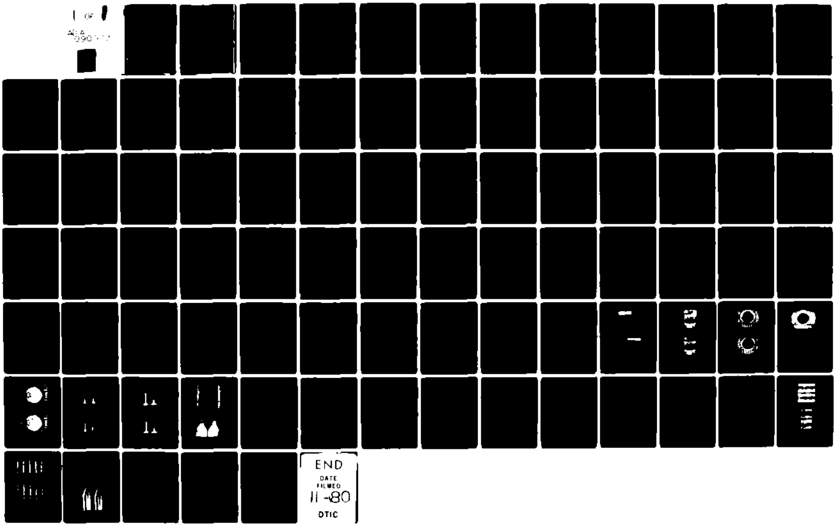

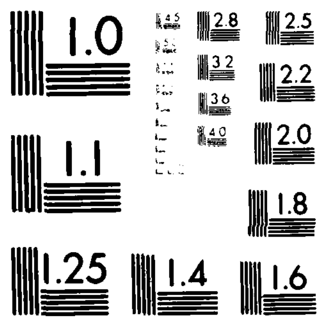

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INFLUENCE OF MICO FUELS ON ENGINE PERFORMANCE, EXHAUST EMISSIONS, AND ENDURANCE

INTERIM REPORT
AFLRL No.125

by

K. Tataiah
and
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U.S. Army Fuels and Lubricants Research Laboratory
Southwest Research Institute
San Antonio, Texas

under contract to

U.S. Army Mobility Equipment
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The influence of Micronized Coal-in-Oil (MICO) fuels on engine performance and exhaust emissions was experimentally studied in a single-cylinder Hatz diesel engine. One of these fuels, which contained 20 wt% coal, was also examined for its effects on engine endurance and wear in a four-cylinder Mercedes diesel engine.

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20. ABSTRACT (Cont'd)

The performance and emissions tests were conducted at twelve different steady-state conditions covering the operating speed-load range of the engine. In each test, the exhaust emissions (including particulates, sulfates, and smoke), crankcase blowby, and temperatures were measured, and brake thermal efficiency and air-fuel ratio were calculated. The results obtained with the single-cylinder engine indicate that the coal in MICO fuel hinders the combustion of the diesel component and decreases the overall brake thermal efficiency of the engine. Although the coal reduces the consumption of diesel fuel component, the total energy consumption is higher.

The exhaust emissions (unburned hydrocarbons, carbon monoxide, oxides of nitrogen, particulates, smoke, and sulfates) increased with the use of coal in the fuel. MICO fuel which contained 2.8 wt% emulsified water further increased the HC, CO, particulates, and smoke emissions. However, the water reduced NO_x and had no effect on sulfate emissions.

The exhaust temperatures with MICO fuels were higher than with diesel fuel. The cast iron rings on the Hatz piston wore rapidly; however, the blowby did not change significantly in 35 hours.

In the Mercedes diesel endurance test, the oil sump temperatures increased rapidly and engine power decreased sharply after 5 to 10 hours of testing. As a result, the engine stalled twice, stopping the test. This phenomenon was observed two times, and the test could not be continued beyond a total period of 14 hours. After disassembly of the engine, it was found that the connecting rod bearing shells, injector valve seats, and cast iron rings were significantly worn. However, stainless steel rings showed no significant wear.

It is evident that significant engine design modifications would be necessary for reliable operation with MICO fuels.

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FOREWORD

The work reported herein was conducted at the U.S. Army Fuels and Lubricants Research Laboratory (AFLRL), Southwest Research Institute, San Antonio, Texas, under Contracts DAAK70-78-C-0001 and DAAK70-80-C-0001. The work was funded through an interagency agreement between the Department of Energy and the Department of Defense the U.S. Army Mobility Equipment Research and Development Command (MERADCOM, DRDME-GL), Ft. Belvoir, VA. Contracting Officer's representative was Mr. F.W. Schaekel, Fuels and Lubricants Division, Energy and Water Resources Laboratory.

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I. INTRODUCTION

In the early decades of this century, many developmental programs were carried out in Germany to utilize coal powder as a diesel engine fuel. Soehngen, in his report[(1)*] to the Energy Research and Development Administration (now the Department of Energy), gives detailed accounts of these programs. The interest in using coal as an IC engine fuel in this country was generated by the energy crisis brought about by various factors in the 1970's. Since then, several studies have been performed in this country in which coal in some form was used to power the diesel engine.[(2-6)]

These studies were limited in scope and were intended to examine a particular aspect of the problem of using coal in an engine designed for diesel fuel. Consequently, the studies were brief and yielded limited information. For example, in an earlier study[(6)] performed by Southwest Research Institute (SwRI) for the U.S. Department of Energy, Pittsburgh Energy Technology Center, it was found that the brake thermal efficiency of an engine with micronized coal-in-oil (MICO) fuel was reduced. In general, it took approximately two Btu's of coal to replace one Btu of diesel fuel. Limitations imposed by the standard engine hardware were also discussed. In the current program, a sequel to the previous SwRI work, the primary objective was to systematically study the effect of MICO fuels, with and without water added, on engine performance, exhaust emissions, endurance, and component wear.

To accomplish these objectives, two different diesel engines were used. The Mercedes Model OM314 engine, which was utilized in the previous study, was used in the endurance testing, while performance studies were carried out on a single-cylinder, four-stroke Hatz diesel engine, Model E-785. In both phases, the dimensions of all the critical engine components were measured before and after testing to determine the wear of these components. Several photographs of the components were also taken to document deposits and changes in surface topography.

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* Superscript numbers in parentheses refer to the list of references at the end of this report.

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In performance tests with the Hatz diesel engine, brake thermal efficiency and exhaust emissions (including particulates and sulfates) were obtained at twelve steady-state conditions with and without water in the MICO test fuels. From the results thus obtained, the effects of coal alone and coal and water together on exhaust emissions and brake thermal efficiency were determined.

II. TEST PROGRAM

A. Test Fuels

The baseline fuel chosen for this study was a locally obtained No. 2-D grade diesel fuel oil. The specifications of this grade fuel, reproduced from ASTM standards, is included in Appendix A as Table A-1.

The MICO fuel was supplied by the Pittsburgh Energy Technology Center in two different coal concentrations. One contained 20 percent coal by weight, while the other had 40 percent coal by weight and a proprietary surfactant. The formulator of these MICO fuels felt that it was unnecessary to add a surfactant for the MICO fuel containing low (20 wt%) concentration of coal. Both the composition and particulate size distribution of the coal used in preparing these MICO fuels are included in Appendix A, Table A-2.

Since one objective of this program was to determine the exhaust emissions and performance of the engine with a MICO fuel in the presence of water, an emulsified diesel fuel containing 5 vol% water was obtained from internal sources at SwRI. It was believed that the water in the MICO fuel would make small reductions in NO_x emissions and might have beneficial effects on smoke and particulates. The water-emulsified diesel fuel contained 20 wt% surfactant composed of 90 wt% "Span 80" and 10 wt% "Tween 80."

Five test fuels were prepared by mixing these three materials (baseline No. 2-D fuel, MICO fuels containing 20 and 40 wt% coal, and emulsified diesel fuel) in appropriate quantities. The final compositions of the fuels are shown in Table 1.

TABLE 1. COMPOSITIONS OF TEST FUELS BY WEIGHT PERCENT

Fuel No.	2-D	Coal	Water	Proprietary Additive	Lecithin	"Span 80" & "Tween 80"
1	100	0	0	0	0	0
2	87.2	0	2.8	0	0	10
3	80	20	0	0	0	0
4	65.86	20	2.8	0.64	0.94	9.80
5	90	10	0	0	0	0

The concentration of water in the second and fourth fuels was kept constant for the purpose of evaluating the variance in the experimental observations by using methods of applied statistics.

The fourth test fuel was prepared from water-emulsified diesel fuel and MICO fuel containing 40 wt% coal. An additional amount of surfactant (lecithin) was added to this formulation to maintain the same ratio between the surfactant and clear diesel fuel. Lecithin is known to be functionally equivalent to the proprietary surfactant used in the MICO fuel containing 40 wt% coal.

B. Test Engines

1. Hatz Engine Description

The Hatz Model E-785 is an air-cooled, vertical, single-cylinder, four-stroke diesel engine equipped with a flywheel fan on the rear of the crankshaft. Main and rod bearings of the engine are of the roller bearing type and are lubricated by centrifugal pressure lubrication. The fuel is injected into the cylinder through a kidney-shaped prechamber to increase dispersion of the fuel. The speed is controlled by a centrifugal governor throughout the speed range. The specifications of the engine are listed in Appendix B, Table B-1.

a. Break-In

The Hatz engine was connected to a dynamometer on the engine stand and was subjected to a 25-hour break-in.

b. Injector Preparation

While the break-in was in progress, a new injector was modified for use with MICO fuels. In this modification, the internal clearance between the valve and its body was increased to eliminate valve sticking. This change increased the fuel leakage rate from almost zero to 60 drops per minute at a pressure of 6895 kPa (1000 psig). After this modification, the injector was tested for cracking pressure, which remained at its initial value of 11,377 kPa (1650 psig).

c. Parameters Measured

To analyze the performance of the engine, the following parameters were measured at every test condition:

(a) Speed
(b) Torque
(c) Weight rate of intake air flow
(d) Weight rate of fuel flow
(e) Intake air temperature
(f) Ambient air temperature
(g) Oil sump temperature
(h) Exhaust pressure
(i) Crankcase pressure
(j) Pressure differential across blowby orifice meter

d. Measurement of Emissions and Particulates

One of the objectives of this program was to study the influence of MICO fuels on exhaust emissions. A dilution tunnel designed and built at SwRI for Environmental Protection Agency research activities was obtained for measuring

particulate and sulfate emissions. A full description and design details of this tunnel can be found in Reference 7. The tunnel was connected to the Hatz engine as illustrated in Figure 1.

The conventional emissions (HC, CO, and NO) were determined from raw exhaust using a heated Flame Ionization Detector (FID) for HC and Nondispersive Infrared (NDIR) instruments for CO and NO. The smoke opacity was measured by an EPA smokemeter at the end of the exhaust pipe. Emission measurements were made at every test condition. In addition, some of the particulate and sulfate measurements were repeated at four test conditions in order to determine the variance of the observations. Also, particulate size distribution was determined for each fuel at one test condition (1800 rpm and 400 kPa) using an Anderson impactor. At this test condition, two exhaust samples of 250 cm^3 were also collected in glass sample bottles and supplied to PETC for analysis.

e. Test Conditions and Run Procedures

At the beginning of this program, it was believed that the objectives could be best accomplished by operating the engine at steady-state conditions over its normal speed and load range with factory-specified injection timing of 26° before top dead center (BTDC). After testing the engine with clear diesel fuel to determine maximum power output, the test conditions given in Table 2 were chosen.

TABLE 2. TEST CONDITIONS AND POWER OUTPUT (kW)

Speed, rpm	Bmep, kPa 150	275	400	525*
1200	0.945	1.733	2.521	2.994
1800	1.418	2.600	3.782	4.916
2400	1.891	3.467	5.042	6.555

* Maximum bmep attained.

The highest load (525 kPa) indicated in the table could not be reached at 1200 rpm with any of the test fuels, and the maximum bmep at this speed was only about 450 kPa. Also, at other speeds (1800 and 2400 rpm), the maximum bmep with MICO fuels was about 5 percent lower than the values in the table.

While conducting the test, the engine was run until all measured parameters had stabilized, and then the necessary readings were taken. Each fuel was

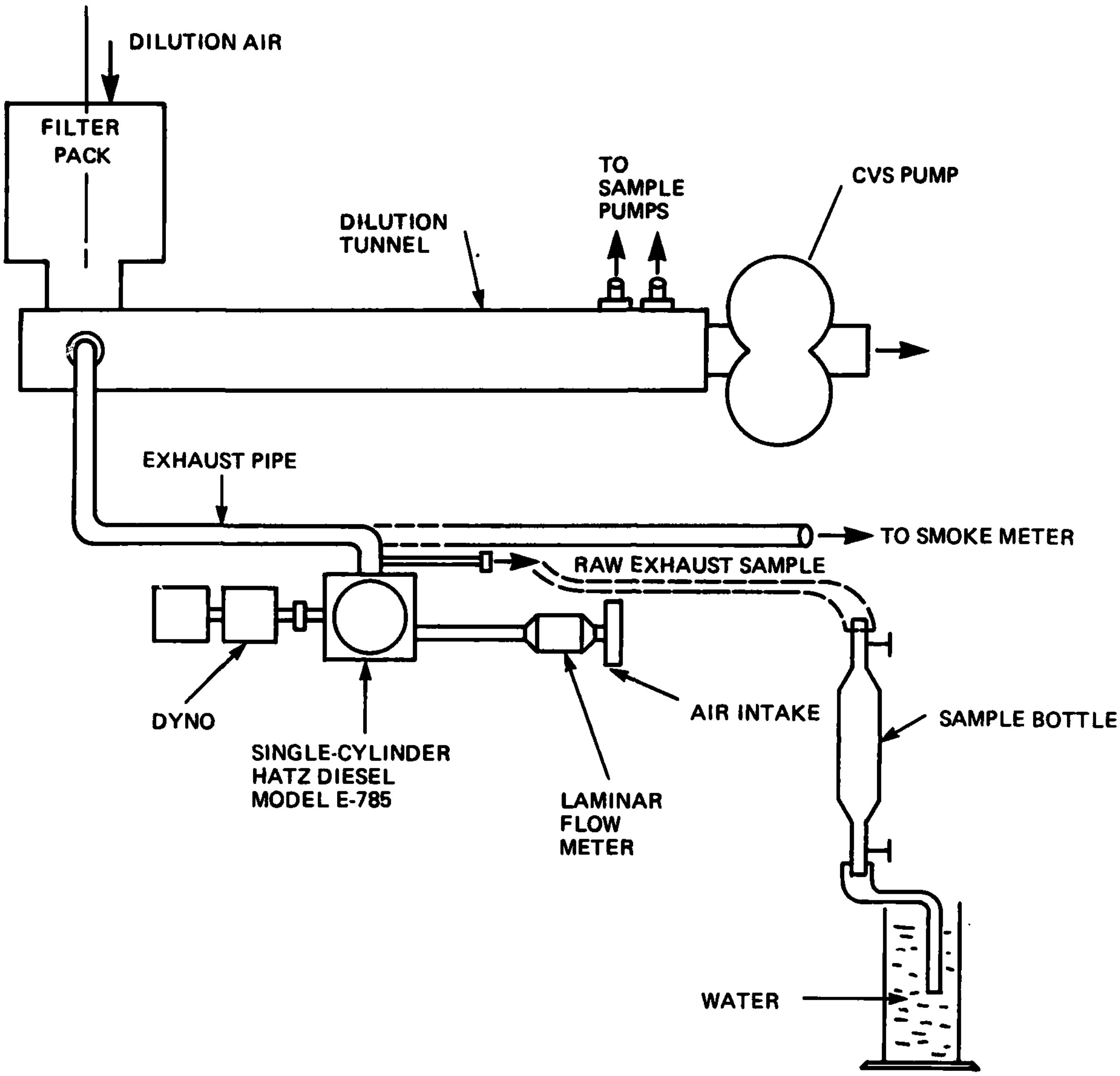

FIGURE 1 - DILUTION TUNNEL FOR EXHAUST PARTICULATE MEASUREMENT WITH HATZ DIESEL ENGINE

tested three times at every test point, except for the MICO fuels containing 10 wt% coal. The first set of 12 tests was performed for measuring particulate and sulfate emissions. The second and third sets were conducted to determine gaseous and smoke emissions, respectively. The performance measurements described earlier were also recorded for each test.

The MICO fuel containing 10 wt% coal was tested only twice for the purpose of separating the relative contributions of coal and diesel components to the power output. Hence, no emission measurements were taken with this fuel.

2. Mercedes Engine Endurance/Wear Test

The Mercedes OM314 is a four-stroke, naturally aspirated, open chamber-type engine equipped with a Bosch fuel injection system. The specifications of the engine are given in Appendix B, Table B-2. In a previous test[6] with MICO fuels involving this engine, the engine was run for 13 hours with indications that wear rates were initially high but decreased with time. In the present program, it was intended to perform additional endurance testing with the same Mercedes engine.

a. Engine Preparation

The OM314 engine was disassembled and overhauled, and the following major parts were replaced with new ones:

(1) piston rings
(2) main bearings
(3) rod bearings
(4) valve tappets
(5) intake valves
(6) fuel pump plungers and barrels
(7) fuel injectors

The following component dimensional measurements were made before the engine was assembled:

(1) cylinder bore diameter
(2) piston diameter
(3) ring gap
(4) ring groove width
(5) wrist pin and bushing diameter
(6) main bearing journal
(7) main bearing clearance
(8) connecting rod journal
(9) connecting rod bearing clearance
(10) valve lifter diameter and length

After making the measurements, the engine was assembled and installed on a test stand equipped with an eddy-current dynamometer. Necessary instrumentation was provided to measure engine speed, torque, fuel flow, oil pressure, and temperatures at various positions on the engines.

b. Break-In

After the engine was installed on the test stand, a break-in procedure was conducted with clear diesel fuel according to the following schedule:

(1) 1 hr at 1000 rpm, no load
(2) 0.5 hr at 1400 rpm, 9.1 hp (1/4 full load)
(3) 0.5 hr at 1400 rpm, 18.2 hp (1/2 full load)
(4) 9 hr at 1400 rpm, 27.3 hp (3/4 full load)

The brake specific fuel consumption (bsfc) was determined at 1-hour intervals during Stage (4) of the break-in procedure. Bsfc decreased from an initial value of 0.53 to 0.44 lb/bhp-hr in the first 5 hours and remained at this latter value during the last 4 hours. At this point, it was judged that break-in was complete. The injectors were then removed from the engine in order to modify them for use with MICO fuel. As with the single-cylinder Hatz engine, this modification included enlarging the diametral clearance between the injector valve and its body. The clearance was considered adequate for use with MICO fuels when the fuel leakage rate was between 30 to 60 drops per minute at a pressure of 6896 kPa (1000 psig).

c. Endurance Test Conditions

Following the break-in and injector modifications, the engine was prepared for the endurance test. Conditions chosen for this test were 2400 rpm and 36 hp (26.85 kW). This speed is lower than the rated speed of 2800 rpm. The maximum power the engine can deliver at 2400 rpm with 2-D fuel is about 72 hp (53.7 kW). It was believed that, under these conditions, the engine would run long enough to determine the wear of critical components with MICO fuel containing 20 wt% coal.

III. TEST RESULTS

A. Hatz Engine

1. Brake Thermal Efficiencies

The brake thermal efficiencies were calculated for each test and are shown in Appendix C. Since most tests were performed three times, the average efficiencies are listed in Table 3.

TABLE 3. AVERAGE BRAKE THERMAL EFFICIENCIES

Speed, rpm	Fuel	Brake Thermal Efficiencies at Bmep, kPa of 150	275	400
1200	2-D	0.206	0.292	0.329
1200	2-D + 2.8 wt% Water	0.219	0.294	0.305
1200	2-D + 20 wt% Coal	0.184	0.257	0.274
1200	2-D + 20 wt% Coal + 2.8 wt% Water	0.194	0.256	0.293
1200	2-D + 10 wt% Coal	0.189	0.259	0.264
1800	2-D	0.205	0.278	0.311
1800	2-D + 2.8 wt% Water	0.200	0.273	0.308
1800	2-D + 20 wt% Coal	0.178	0.250	0.272
1800	2-D + 20 wt% Coal + 2.8 wt% Water	0.188	0.259	0.284
1800	2-D + 10 wt% Coal	0.186	0.243	0.273
2400	2-D	0.164	0.249	0.289
2400	2-D + 2.8 wt% Water	0.174	0.239	0.300
2400	2-D + 20 wt% Coal	0.156	0.220	0.256
2400	2-D + 20 wt% Coal + 2.8 wt% Water	0.158	0.230	0.274
2400	2-D + 10 wt% Coal	0.152	0.222	0.242

The results of Table 3 are plotted in Figure 2 (for 1200 and 2400 rpm), which shows the percent change in brake thermal efficiency of various fuels from the baseline 2-D fuel.

The addition of water to 2-D fuel results in an improvement in brake thermal efficiency, particularly at low loads, and also slightly increases the thermal efficiency of the coal-slurry (20 wt% coal) fuel.

The coal fuels always show a lower thermal efficiency than the baseline 2-D fuel, with this deficiency generally increasing with increasing load. Several things are notable from these results: the deficiency in thermal efficiency is not much affected by engine speed, and there is not much difference in the efficiency between the 2-D + 20 wt% coal and the 2-D + 10 wt% coal mixtures. Further, the latter mixture actually reduces the efficiency of the combustion of the diesel fuel component, since, if the coal did not burn at all, the thermal efficiency would be reduced by about 7.3 percent. Actual reductions were consistently greater than this.

The 2-D + 20 wt% coal mixture resulted in some useful coal combustion, since complete absence of coal combustion in this mixture would produce a 15-percent reduction in brake thermal efficiency, compared to the 2-D baseline results. This efficiency reduction is exceeded only once, at 1200 rpm and maximum load.

As will be discussed more fully, the evidence points to late combustion of the coal fraction in these mixtures. The fact that efficiency of the mixtures is not much affected by engine speed leads to the hypothesis that the problem is not due so much to the slow combustion rate of the coal particles, but more to the nature of the slurry itself. In the fuel spray produced by the injection nozzle, the liquid droplets have a size on the order of 10 micrometers in diameter. Since the mean coal particle size is about five times smaller, the coal particles must be contained within the diesel fuel droplets. Ignition would be expected to occur normally, and combustion of the liquid fuel should proceed in much the conventional manner, with vaporization of liquid fuel occurring along with mixing of the vapor with air and simultaneous burning.

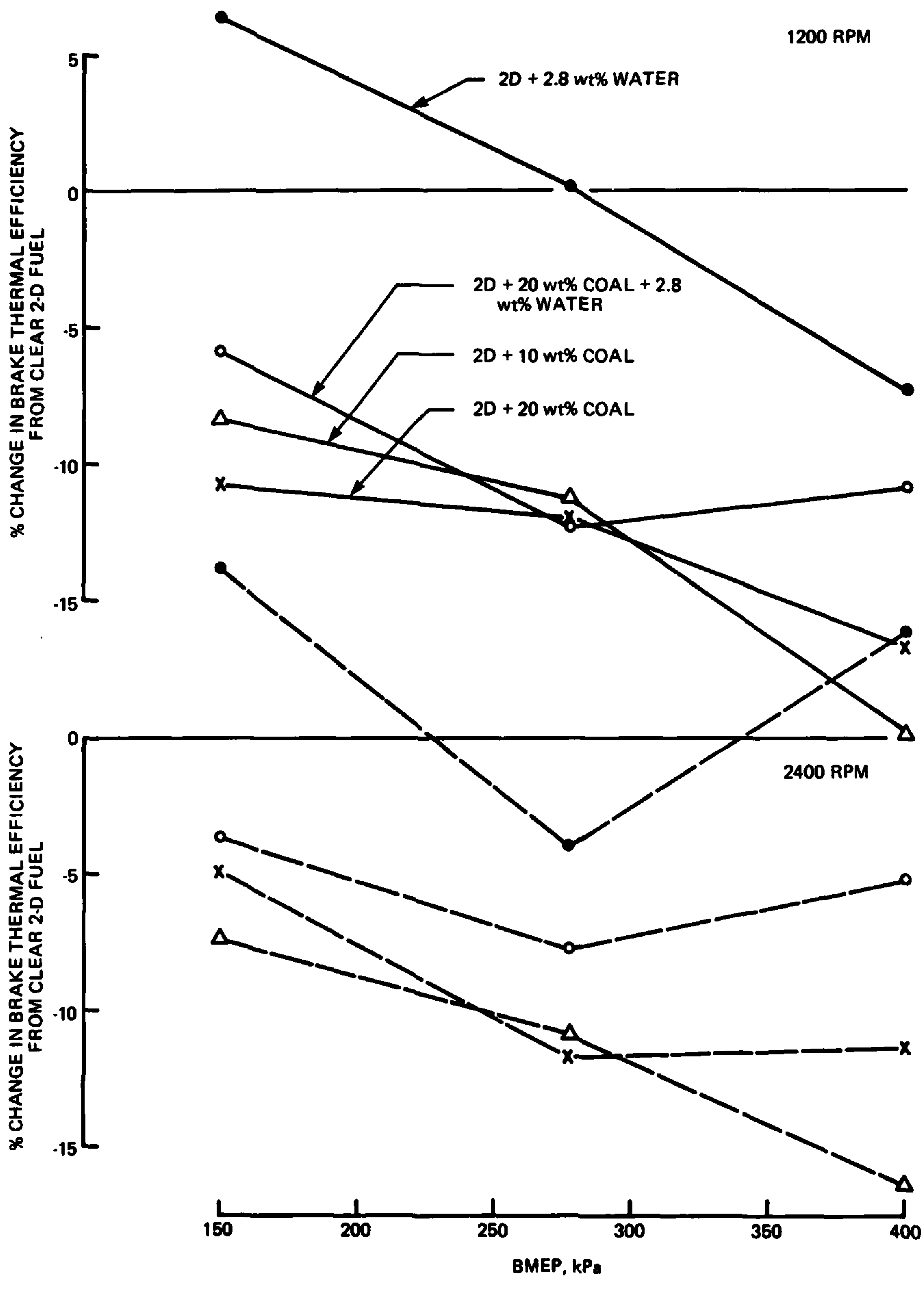

FIGURE 2 - CHANGE IN HATZ ENGINE THERMAL EFFICIENCY FOR VARIOUS SPEEDS, LOADS, AND FUEL TYPES

In this hypothesis, the coal is left to burn last, after the diesel component has partially exhausted the oxygen content of the cylinder. Under these difficult conditions (low oxygen content, reduced temperature due to gas expansion by piston motion), it would not be surprising if a substantial percentage of the coal burned too late in the expansion stroke to produce much useful power.

The small effect of engine speed tends to reinforce this theory since, if late burning was due only to the long time required to burn a coal particle, lower speeds should show higher efficiencies.

However, the theory does not explain the small effect of the weight percent of coal in the slurry, or why the 10 wt% coal mixture has an efficiency lower than would be expected if the coal contributed nothing to developed (shaft) power.

Figure 3 shows a different presentation of the results of Table 3. Here the fuel heat input for the baseline 2-D fuel is compared to the 2-D + 20 wt% coal mixture. From Figure 3, it is seen that the coal provides power contribution sufficient to reduce the amount of 2-D fuel needed at a given engine speed and load. Therefore, if the use of a coal-diesel fuel slurry is evaluated on the basis of the fuel energy required to produce a certain amount of power, it is less effective than diesel fuel alone. If the intent is to save diesel fuel without regard for the total energy input to the engine, then the coal-diesel fuel slurry accomplishes this to a greater or lesser extent, depending upon engine speed and load. The results for the 2-D + 10 wt% coal indicate that diesel fuel consumption is adversely affected with this fuel.

Some of the coal energy might have been lost through the exhaust in unburned coal, the increase in exhaust particulates with MICO fuels were determined and compared with coal intake. These results are shown in Table 4.

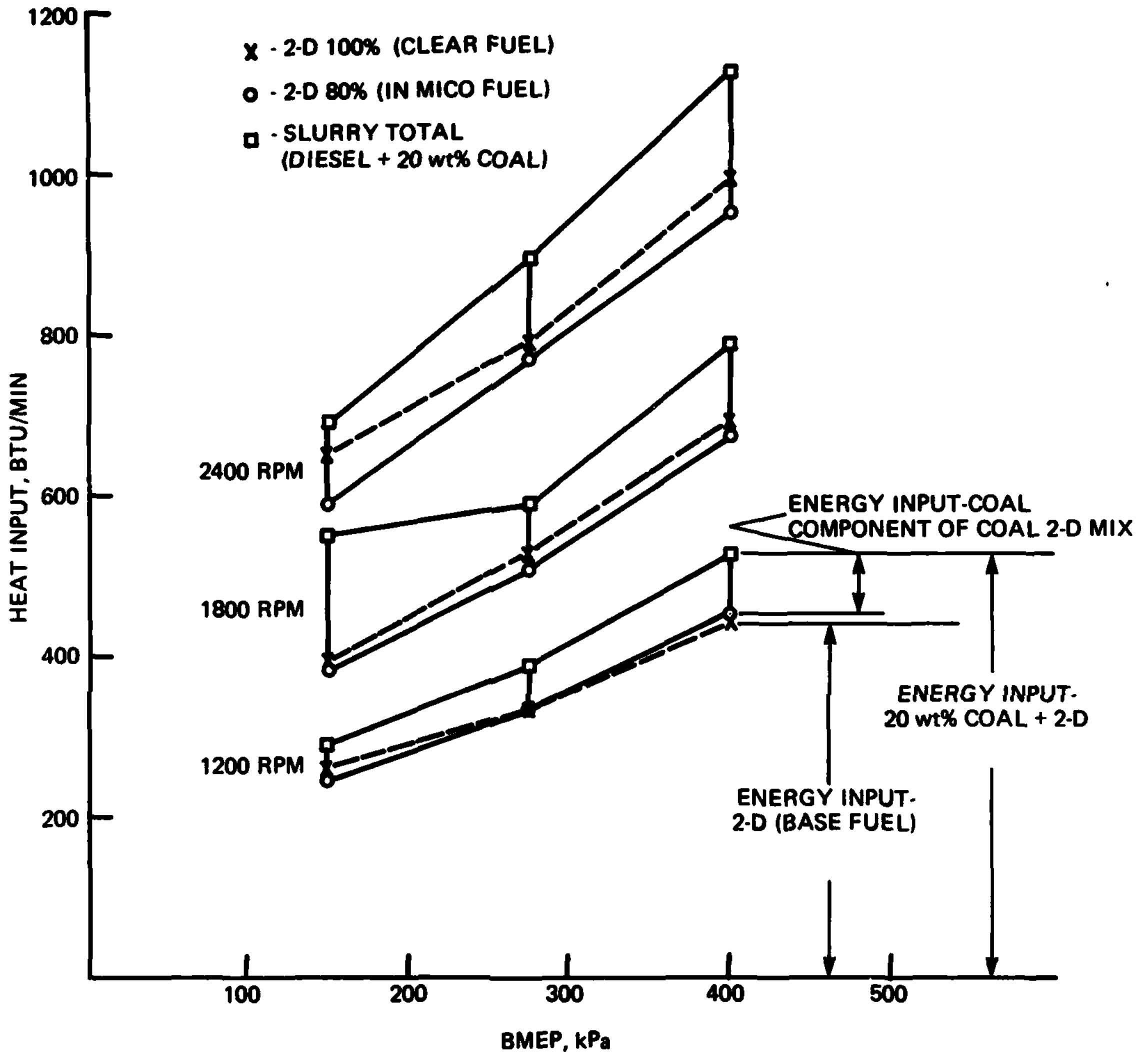

FIGURE 3 - HEAT INPUT FOR MICO AND CLEAR (BASE) FUELS AT VARIOUS ENGINE SPEEDS AND LOADS

TABLE 4. FUEL CONSUMPTION AND PARTICULATES WITH BASELINE AND A MICO FUEL CONTAINING 20 WT% COAL

		Baseline Fuel		MICO Fuels			Increase in
Speed, rpm	BMEP, kPa	2-D, g/min	Part, g/min	2-D, g/min	Coal, g/min	Part, g/min	Particulates, Coal %
1200	150	5.58	0.005	6.23	1.56	0.066	3.9
	275	8.13	0.014	8.01	2.00	0.112	4.9
	400	9.44	0.029	11.06	2.77	0.141	4.0
1800	150	9.27	0.045	9.78	2.44	0.148	4.2
	275	12.32	0.037	12.50	3.12	0.222	5.9
	400	16.13	0.068	16.84	4.12	0.365	7.1
2400	150	16.00	0.130	14.57	3.64	0.225	2.6
	275	19.23	0.149	18.97	4.74	0.262	2.4
	400	24.15	0.136	24.30	6.08	0.355	3.6

The measurements of particulates were not highly repeatable, and these increases have to be viewed with some reservation. The variance of these measurements are discussed separately in the section entitled "Particulates." However, the measurements indicate sizable increases and are shown as a percent of coal intake in the last column. These increases varied between 2.4 and 7.1 percent. However, if the increases were due to unburned coal, only a small fraction of the difference in brake thermal efficiencies would be accounted for.

In the coal analysis of Appendix A, the ash content of the coal is about 9 percent by weight, or in a slurry containing 20 percent coal by weight, about 1.8 percent of this mixture is coal ash. Since ash is by definition incombustible material, part of the increase in exhaust particulates can thus be accounted for.

The consumption of the diesel fuel component in the emulsified fuel containing 2.8 wt% water was almost equal to that for the baseline tests with 2-D fuel, as shown in Figure 4.

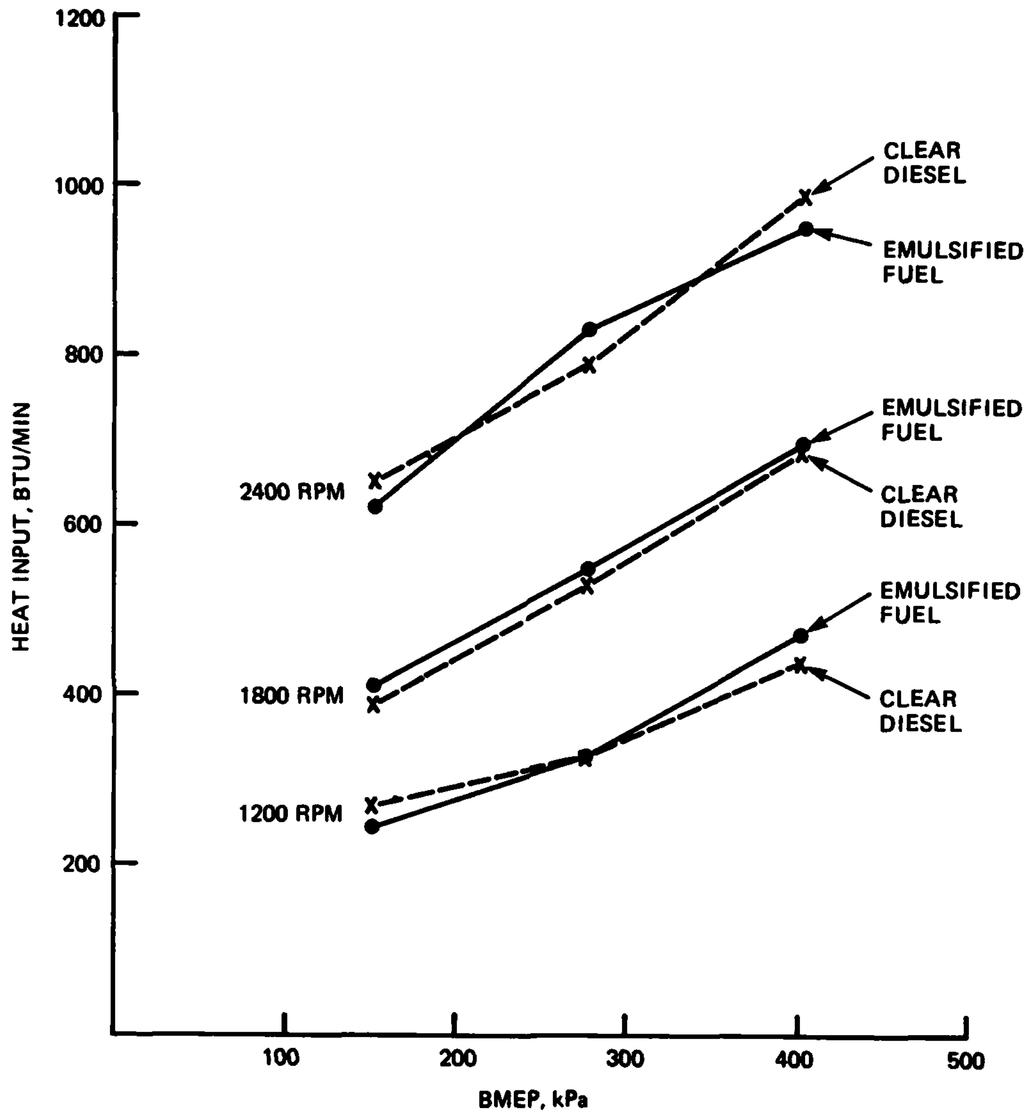

FIGURE 4 - HEAT INPUT FOR WATER EMULSIFIED AND CLEAR (BASE) FUELS AT VARIOUS ENGINE SPEEDS AND LOADS

2. Exhaust Temperatures and Combustion of MICO Fuel

The exhaust and intake temperatures, along with various other temperatures, were recorded for every test. The difference (ΔT) between these two temperatures is plotted versus engine load in Figures 5 through 7. The effect of coal on the exhaust-minus-intake temperature differential is clearly seen in these figures.

Notable is the fact that the presence of coal increased exhaust temperatures significantly, which is consistent with the finding of lower brake thermal efficiency with the slurry fuel. The most likely reason for these effects on efficiency and exhaust temperature is late burning of the coal fraction, with the heat release from the coal occurring too late to contribute to shaft power. This is verified by the fact that the spread in the curves increases over the load range as the speed is increased, i.e., less time available for combustion.

On the other hand, it is interesting to recall that the increase in exhaust particulates is relatively small compared to coal consumption (see section above). If late-burning is the cause of reduced efficiency, a greater increase in exhaust particulates would be intuitively expected. Stated another way, an explanation based solely upon late burning of the coal also requires the supposition that nearly all of the coal burns late, but burns almost completely to ash before the exhaust gases are sampled. It is possible that the coal particles remaining unburnt or partially burnt at the end of the expansion stroke are, in large part, consumed in the turbulent mixing in the vicinity of the exhaust valve during exhaust blowdown at the end of the expansion stroke. Such mixing may be required to bring the coal particles in contact with the relatively small amount of oxygen remaining in the gases after diesel fuel combustion.

In this regard, the exhaust pipe was removed from the cylinder head of the Hatz engine, the test cell was darkened, and the engine was run at full load with the 20-percent coal mixture. Only a very few luminous particles could be seen emerging from the exhaust port, which indicates that if final burning does occur during blowdown, the combustion is completed very quickly; otherwise, burning particles would be visible at the exhaust port exit.

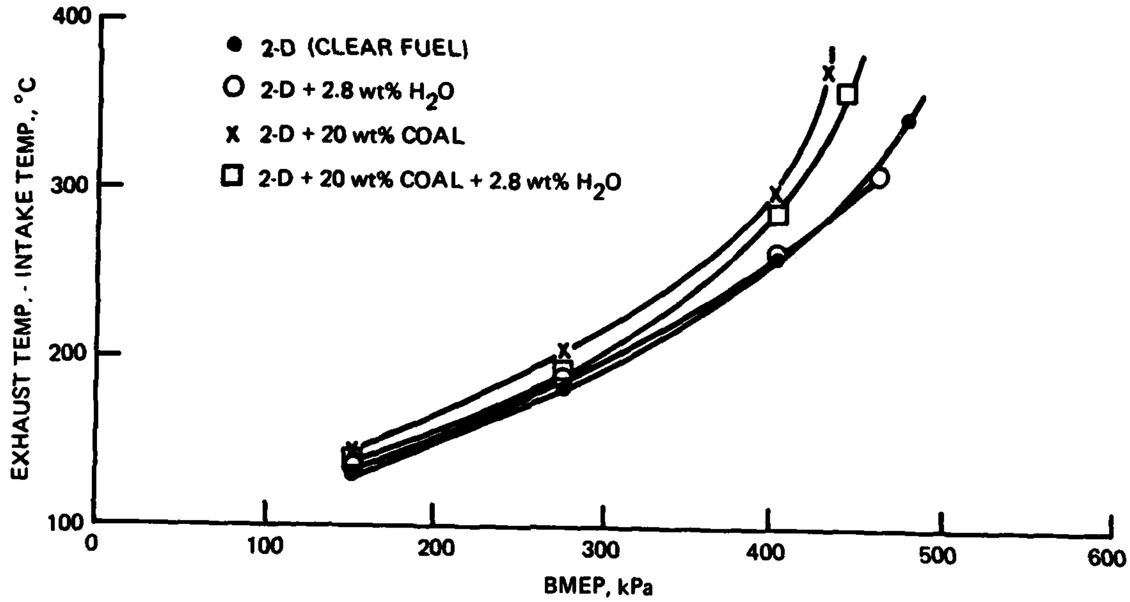

FIGURE 5 - EXHAUST MINUS INTAKE TEMPERATURE AT 1200 RPM, VARIOUS LOADS

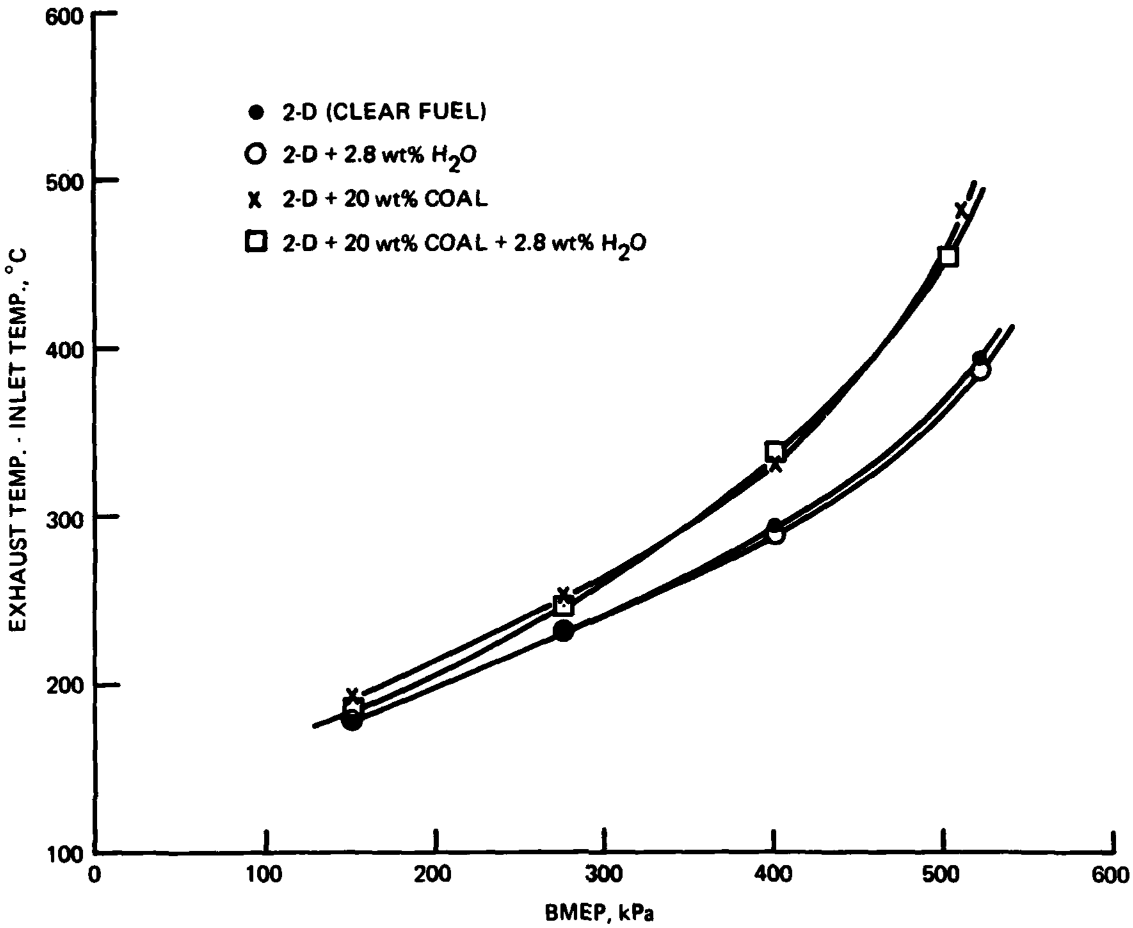

FIGURE 6 - EXHAUST MINUS INTAKE TEMPERATURE
AT 1800 RPM, VARIOUS LOADS

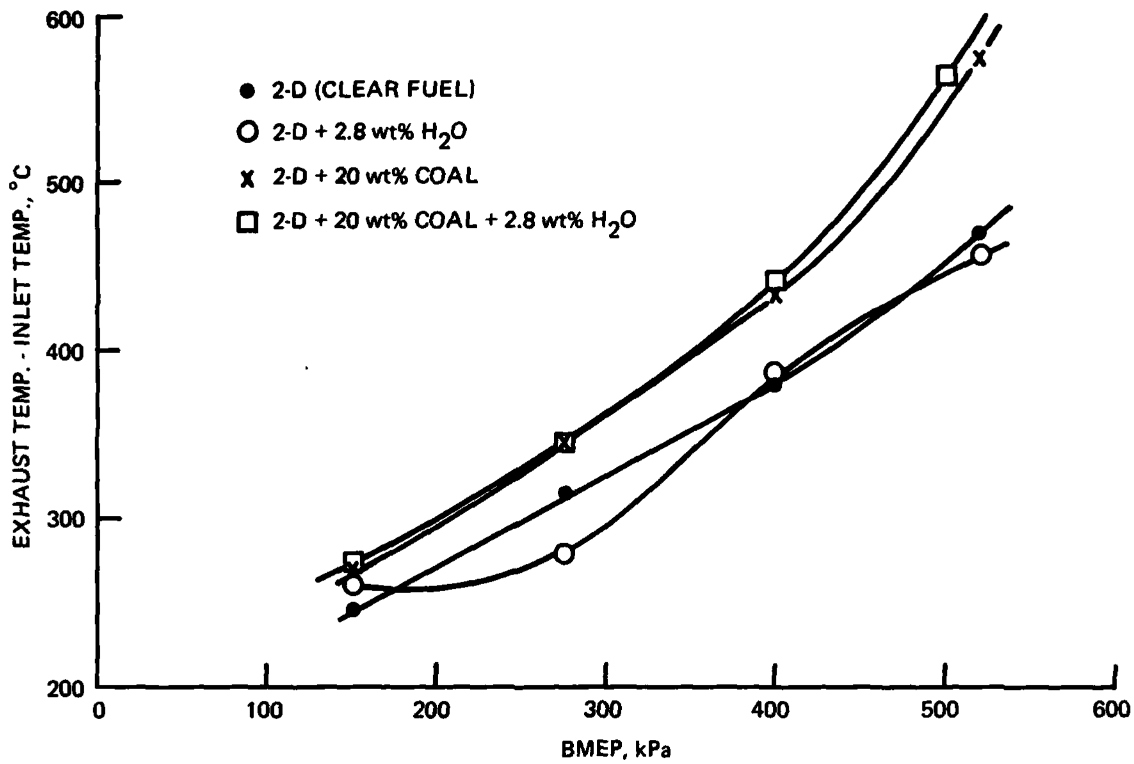

FIGURE 7 - EXHAUST MINUS INTAKE TEMPERATURE
AT 2400 RPM, VARIOUS LOADS

Analysis of cylinder pressure traces showed that ignition delay was not affected by the presence of coal, a result expected from the coal-in-droplet hypothesis previously explained.

3. Blowby

The blowby from the crankcase was measured at every test condition by an ASTM sharp-edged orifice flowmeter, and the blowby data are plotted as a function of engine operating time in Figures 8 through 10. The change in blowby at any one speed was so slight that it can be ignored for all practical purposes.

4. Regulated Emissions

Exhaust unburned hydrocarbon data are shown in Figure 11. The addition of coal increased exhaust hydrocarbons, and the addition of water to the coal-diesel fuel mixture further increased them. Water added to diesel fuel (without coal) had little effect upon hydrocarbons.

Figure 12 shows carbon monoxide emissions, and the characteristics described for hydrocarbons are also valid for CO.

Figure 13 shows NO emissions for the Hatz engine. The addition of coal to 2-D fuel increases NO, while the addition of water to either clear 2-D fuel or to the slurry generally decreases NO. These effects are clear at 2400 rpm, becoming somewhat less discernible at lower engine speeds.

These results are consistent with the hypothesis that the coal fraction in the slurry fuel burns late during the expansion stroke. In oxidizing either hydrocarbons or CO, the efficiency of oxidation is reduced by shorter oxidation times and lower temperatures. Late burning produces both these conditions, and the addition of water further reduces gas temperature. Therefore, if late burning is the cause of the observed effects, the added quantities of hydocarbons and CO in the exhaust originate mainly from combustion of the coal.

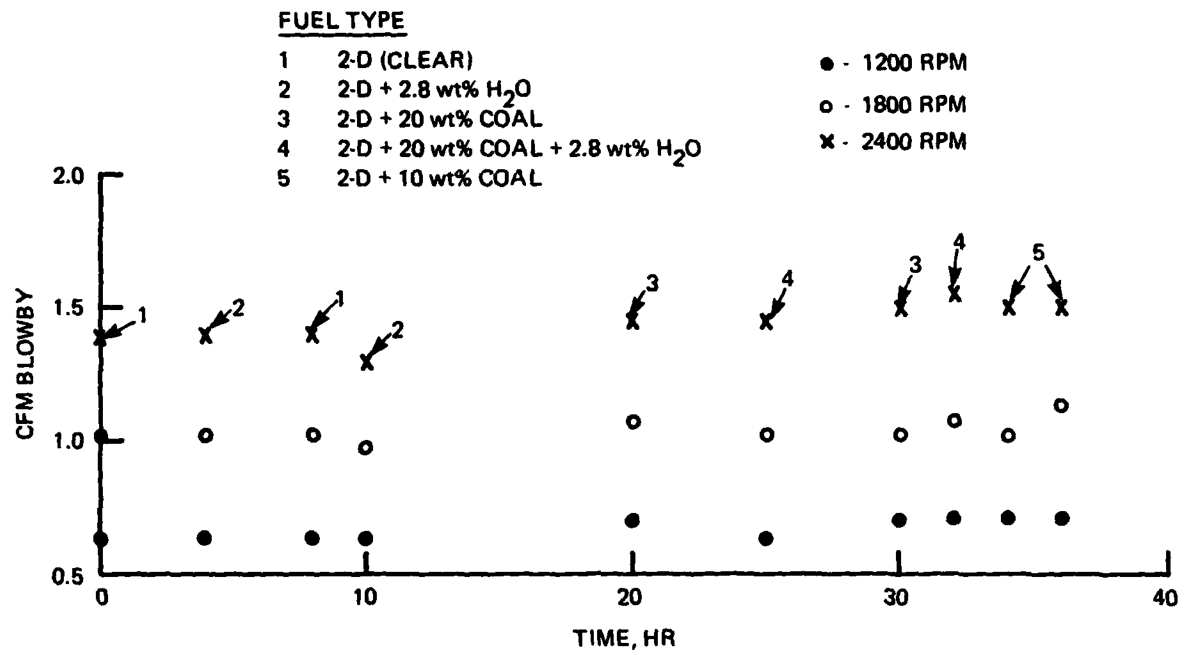

FIGURE 8 - CRANKCASE BLOWBY AS A FUNCTION OF OPERATING TIME FOR VARIOUS FUELS AND ENGINE SPEEDS, HATZ ENGINE AT 150 kPa BMEP

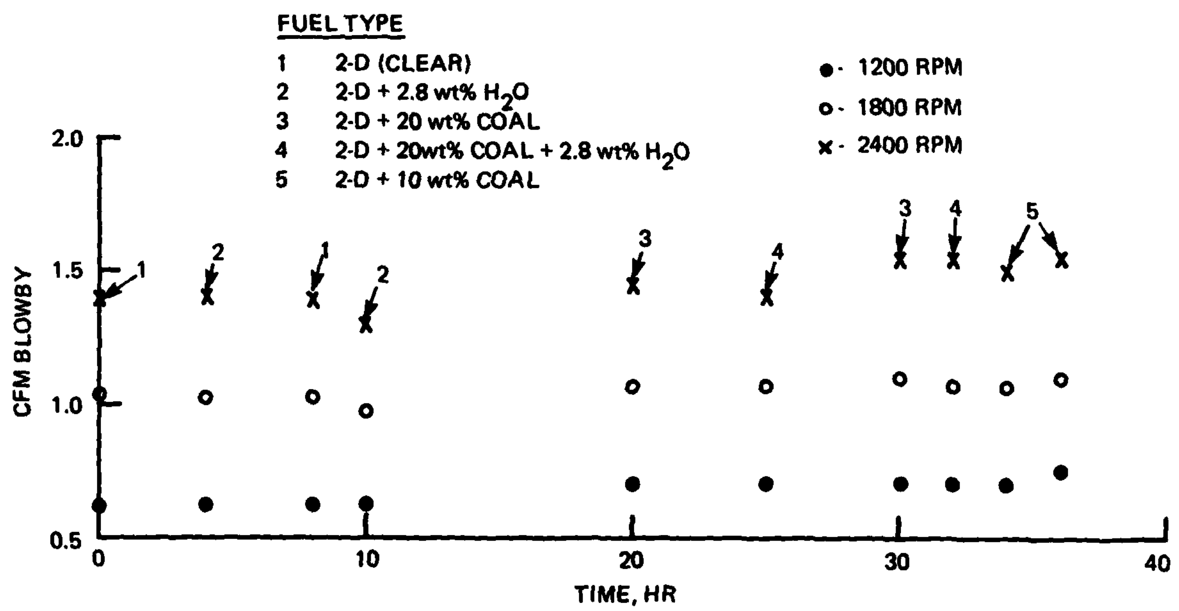

FIGURE 9 - CRANKCASE BLOWBY AS A FUNCTION OF OPERATING TIME FOR VARIOUS FUELS AND ENGINE SPEEDS, HATZ ENGINE AT 275 kPa BMEP

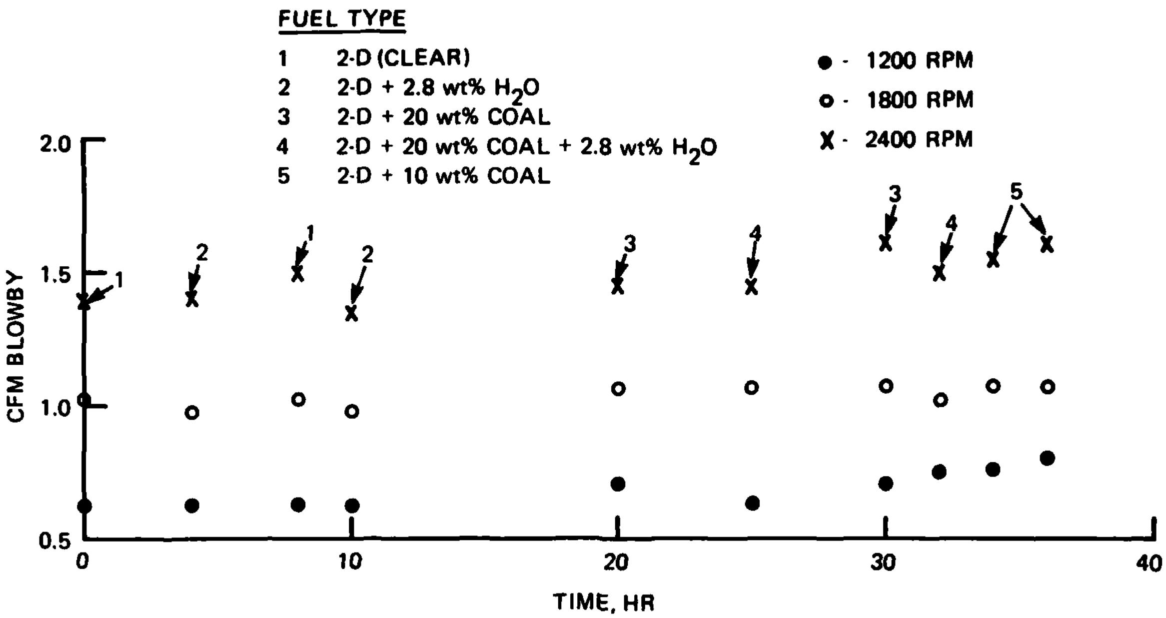

FIGURE 10 - CRANKCASE BLOWBY AS A FUNCTION OF OPERATING TIME FOR VARIOUS FUELS AND ENGINE SPEEDS, HATZ ENGINE AT 400 kPa BMEP

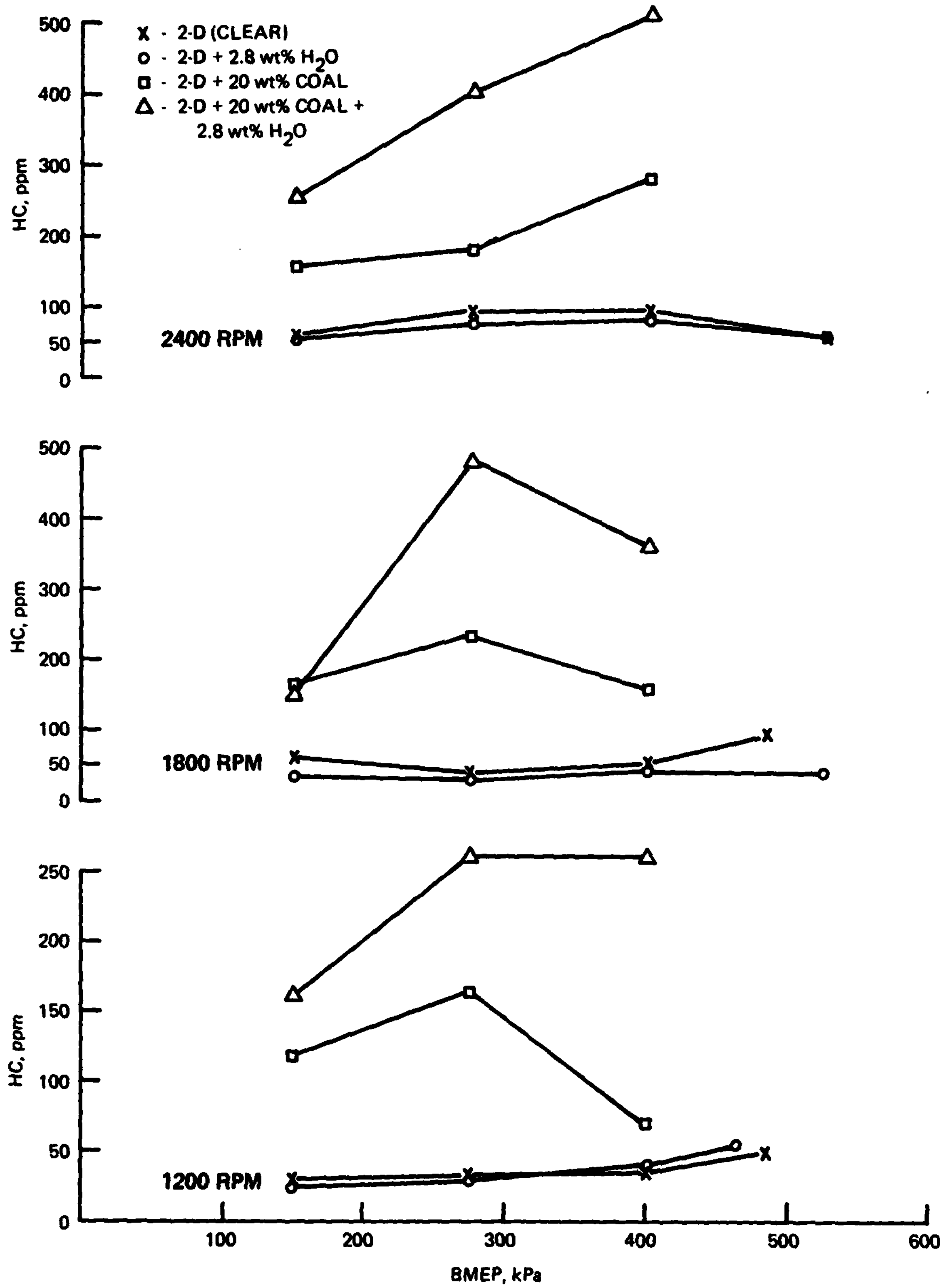

FIGURE 11 - UNBURNED HYDROCARBONS CONCENTRATIONS FOR HATZ ENGINE

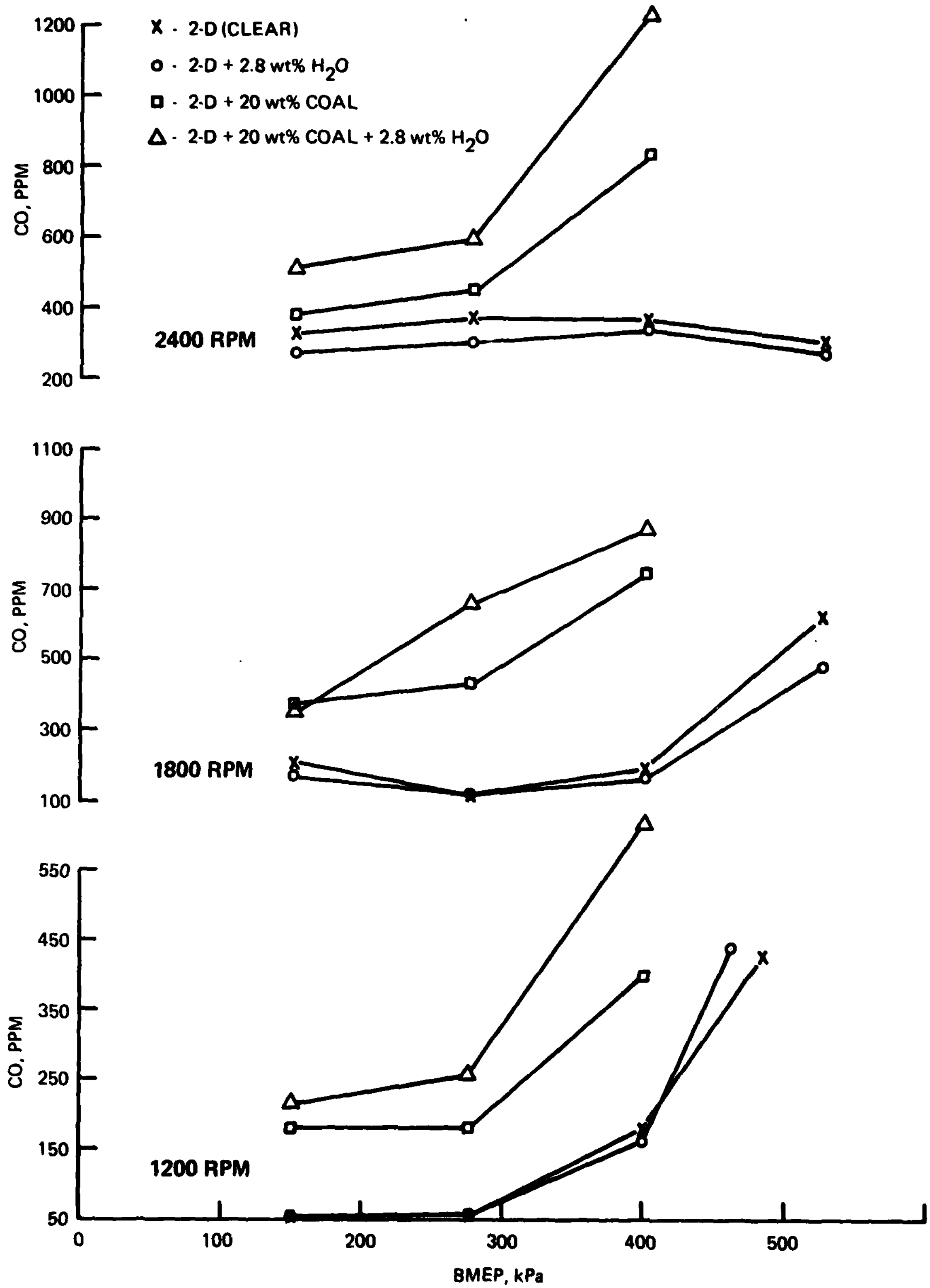

FIGURE 12 - CARBON MONOXIDE CONCENTRATIONS FOR HATZ ENGINE

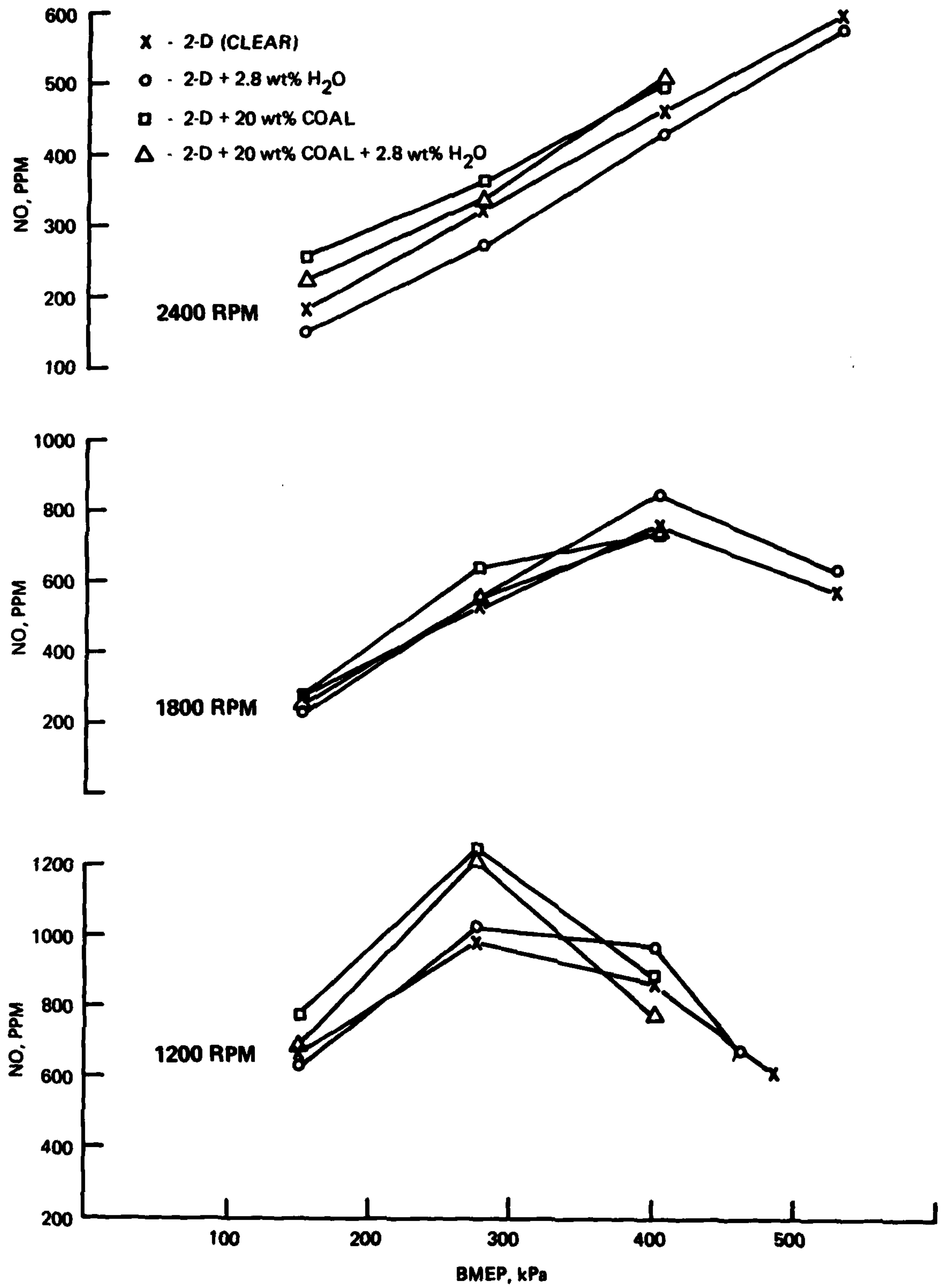

FIGURE 13 - NITRIC OXIDE CONCENTRATIONS FOR HATZ ENGINE

The NO increase could be partially due to the fuel bound N.

5. Particulates

Both the particle size distribution and total mass emitted from the engine were measured. First, the results of particle size distribution will be discussed.

a. Fuels Effect on Size Distribution

These tests were performed for each fuel at one test condition (1800 rpm and 400 kPa) using an Anderson impactor. The results obtained are shown in Figure 14. Most (about 82 percent) of the particles for the base fuel were less than 0.42 micrometer in diameter. About 18 percent of the particles fell in the range of 0.42 to 10.9 micrometers in diameter. In the case of MICO fuels, about 50 percent of the particles were in this larger range. This is probably due to the presence of either unburned coal or coal ash in the exhaust. There was no significant effect of water on particle size distribution.

b. Effect on Particulate Mass

The particulate mass measurements were made using a filter in the sample line from the dilution tunnel. Tests were done at two levels (conditions) for each controlled variable (BMEP and concentration of coal and water). In addition, a set of replicate tests was performed at four speed/load conditions to determine the variance of the observed results. All the results are shown in Appendix E. It was found that the results of replicate tests varied significantly. Therefore, conventional plots showing the influence of various parameters on particulate emissions would have little significance. Instead, the effect (increase or decrease) of coal, water, and engine load were analyzed using the methods of applied statistics. A sample calculation of the effects is included in Appendix E, and the results of these calculations are summarized below. The numbers in the columns indicate increase or decrease in particulate matter in g/kW-hr for each affecting variable or variables in the range (between two levels) tested.

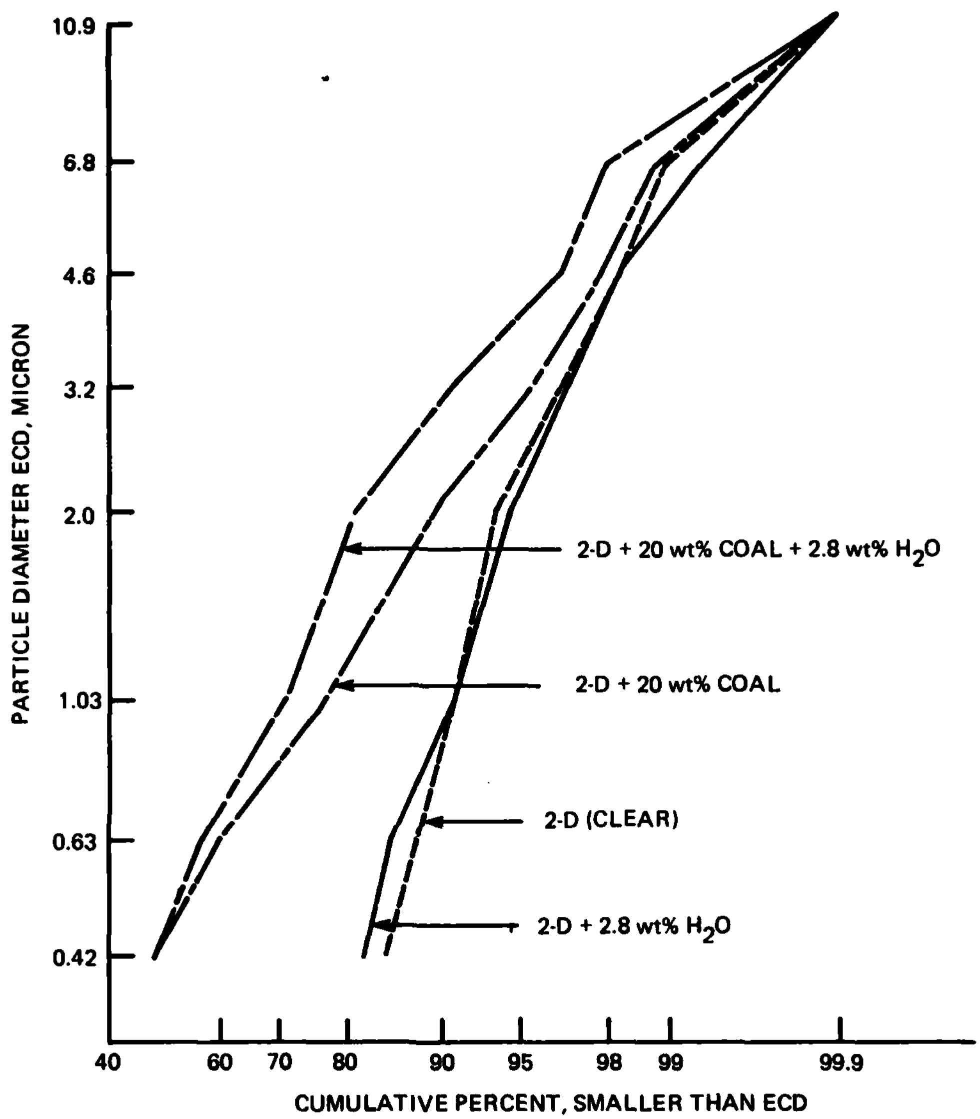

FIGURE 14 - PARTICULATE SIZE DISTRIBUTION FOR HATZ ENGINE AT 1800 RPM, 400 kPa BMEP

	E*, g/kW-hr	
	1200 rpm	2400 rpm
Main effect of water	0.139	0.625
Main effect of BMEP	-0.171	-2.765
Main effect of coal	3.06	3.93
Interaction effect of water and BMEP	0.0242	-0.14
Interaction effect of water and coal	0.0010	0.80
Interaction effect of BMEP and coal	-0.469	0.90
Interaction effect of water, BMEP, and coal	0.096	-0.89
95% confidence interval	E ± 0.244	E ± 0.475

* E denotes effect, negative sign indicates a reduction.

An effect is considered to be significant only when its absolute value is large enough such that the 95-percent confidence interval for its mean does not include zero. For example, the main effect of coal at 1200 rpm was calculated to be 3.06 g/kW-hr, while the 95-percent confidence interval for its mean ranged from +2.816 to +3.304 g/kW-hr. This interval does not include zero, and the effect is said to be significant. In the case of the main effect of water at 1200 rpm, the 95-percent confidence interval is from -0.105 to +0.383 g/kW-hr and includes zero. Therefore, the main effect of water is said to be insignificant.

Therefore, from these results, it is found that the following effects were statistically significant: At 1200 rpm, only the main effect of coal and the interaction effect of bmep and coal; at 2400, all main and interaction effects <u>except</u> the interaction of water and bmep. Thus, engine speed caused the significance of the effects to vary.

6. Sulfates

Although it is known that sulfur in the fuel directly influences the sulfate emissions, it was desired in this program to determine the effect of other experimental variables on sulfates. The concentrations of sulfur in the base (clear diesel) and MICO fuels were, respectively, 0.23 and 2 wt%. Therefore, sulfates were measured along with the particulate matter for every test fuel. The data are listed in Appendix F, and a summary of the effects of various

factors, calculated by the same statistical technique outlined above, is given below:

	E*, g/kW-hr	
	1200 rpm	2400 rpm
Main effect of water	5.32	14.96
Main effect of BMEP	-79.57	-68.90
Main effect of coal	135.35	104.90
Interaction effect of water and BMEP	-2.54	-10.90
Interaction effect of water and coal	2.15	13.70
Interaction effect of BMEP and coal	-71.95	-60.10
Interaction effect of water, BMEP and coal	-4.48	-15.10
95% confidence interval	E ± 18.97	E ± 22.9

* E denotes effect; negative sign indicates a reduction.

Thus, it can be seen that these effects were significant: At both 1200 and 2400 rpm, the main effect of bmep and coal, and the interaction of bmep and coal. Hence, engine speed was not a factor in whether or not a given effect was significant.

7. Smoke

The amount of smoke in diesel exhaust is normally a function of air-fuel ratio. Therefore, Figure 15 shows the smoke results (in percent opacity) with respect to equivalence ratio, which is defined as the ratio of stoichiometric to actual air-fuel ratio. These results were further grouped on the basis of engine speed, and are shown in three different plots. This was done to clearly gauge and compare the influence of the test fuels on smoke.

The point of interest in Figure 15 is the relatively small increase in smoke opacity produced by the coal, as compared to the clear 2-D fuel at the same equivalence ratio. This is partially due to the larger particle sizes in the slurry-fueled exhaust, which for the same mass flow rate, produce less opacity change than do smaller particles.

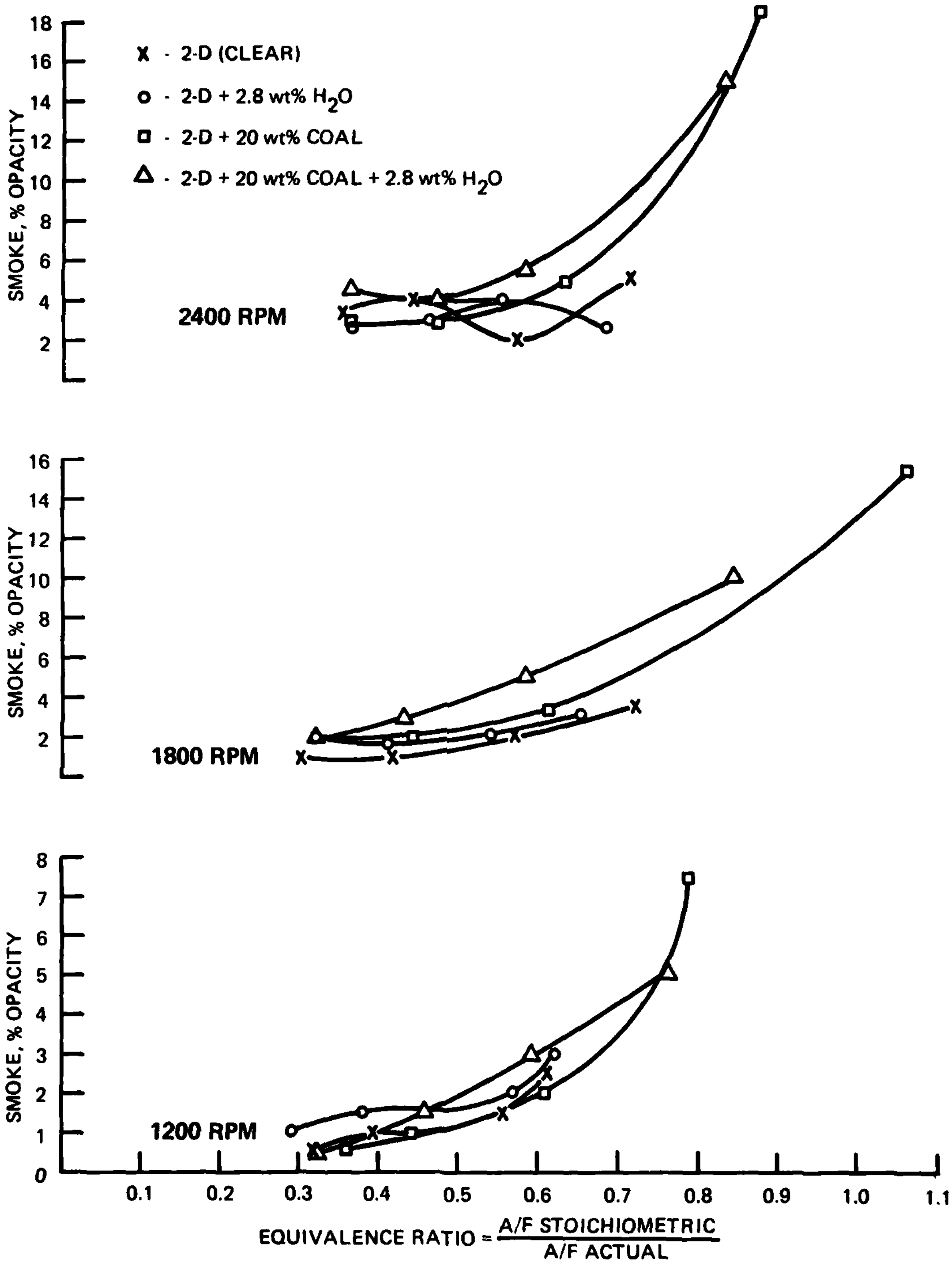

FIGURE 15 - EXHAUST SMOKE OPACITY FOR HATZ ENGINE

8. Wear of Hatz Engine Components

The wear of critical engine components was of interest in this program because the coal component in the MICO fuel and the ash that results from combustion of the coal are both abrasive. After engine break-in, and before testing commenced, dimensional measurements for the following Hatz engine components were made:

(1) cylinder bore diameter
(2) piston diameter
(3) piston ring thickness
(4) piston ring groove width
(5) wrist pin diameter.

The engine accumulated about 60 hours of running time on the MICO fuels. The measurements were repeated after the tests were completed, and the results are shown in Appendix G. There was substantial wear of the bottom three rings [about 0.20 in. (5 mm) gap] and the top ring groove in the piston. The bottom three rings were made of cast iron, while the top ring was made of chrome. Also, slight wear [0.015 in. (0.38 mm)] was noticed at the bottom of the cylinder bore and at the top of the piston. The main and rod bearings were of roller bearing type, and no dimensional measurements could be made. However, no abnormal wear was evident.

To document the surface damage, photographs were taken of several components before and after the test (Appendix G, Figures G-1 through G-15). These components include piston, wrist pin, cylinder, head, intake and exhaust valves, fuel pump plunger, and injector valve. Of all these components, only the fuel pump plunger and injector valve (Appendix G, Figures G-14 through G-15) show some surface modification and wear. However, at test completion, the fuel system could still operate with MICO fuels.

B. Endurance and Wear of Mercedes Engine

The endurance test on this engine was performed with MICO fuel containing 20 wt% coal under a steady-state condition of 2400 rpm and 36 bhp (26.8 kW).

This power is about 50 percent of maximum for the Mercedes at 2400 rpm. During the test, the engine speed, load, fuel flow, oil pressure, blowby, and several temperatures were measured. These temperatures include cooling water (in and out), oil sump, inlet air, and exhaust. With minor difficulties, the engine was able to run for five hours; at the end of this time, the engine began losing power and finally came to a stop. During the last 20 minutes, it was observed that the oil pressure dropped from 70 to 35 psi, and the oil sump temperature increased from 225°F(107°C) to 356°F(174°C).

To determine the factors that caused this unscheduled shutdown, an inspection was performed, and it was discovered that (1) the oil level in the sump was about 1.5 inches (38.1 mm) higher than the initial level, (2) one of the injectors was stuck open and, (3) the valves in the others were very tight. Dilution of the oil was caused by fuel leakage, either from the fuel pump or from the malfunctioning injectors. The increase in sump temperature could have resulted from the reduced viscosity caused by this dilution, since low oil viscosity increases friction (heat) in the engine.

To reduce the probability of the injector valves sticking again, valve stem clearance was further increased to obtain a leakage rate of about 120 drops per minute at 6895 kPa (1000 psi). The oil in the crankcase was changed, and endurance testing was resumed. After a period of 9 hours, the same problems of low power and high oil temperature recurred. This time the oil level in the sump was only 0.5 in (12.7 mm) above the initial level. The injectors were removed and checked in a tester. All nozzles were leaking before the cracking pressure was attained, and the spray pattern was abnormally narrow.

It was believed that further endurance testing with MICO fuel would not be productive. However, to isolate the causes for this failure, the engine was operated under the same conditions as in the endurance test, but with clear 2-D diesel fuel. The engine ran on clear fuel without excessive oil temperature for eight hours. At the end of this time, the oil in the sump was 0.25 in. (6.35 mm) lower than the initial level. At this time, it was believed that the engine would run on clear diesel fuel without problems for a longer period; hence, the test was discontinued.

After termination of the endurance test, the engine was disassembled, and the same component measurements were made again. The initial and final measurements are shown in Appendix H. The results indicate that no excessive wear occurred on any component except on Nos. 2, 3, and 5 rings of every piston. These rings are made of cast iron and had worn very badly, showing more than 0.1-in. (2.54-mm) gaps. The same excessive wear also occurred on cast iron rings in the Hatz engine.

Although the dimensional measurements did not reveal any other wear problems, visual inspection showed that the connecting rod big end bearings were badly worn. Photographs of these bearings, the main crankshaft bearings, fuel pump plungers, injector valves, and injector tips are shown in Appendix H, Figures H-1 through H-6. Main bearings also show some wear (Figure H-2), with the copper alloy beneath the flash layer being exposed. Two photographs were taken of the fuel pump plunger (Figures H-3 and H-4). These show the characteristic wear pattern on the bottom half of the plunger, as previously observed[6] with this engine.

The photographs in Figure H-5 indicate that the main bodies of the injector valves showed no wear. However, the tips of a couple of valves (shown enlarged in Figure H-6) indicate that there was some wear on the valve seats, which might be the cause for the previously mentioned abnormal spray pattern from the injectors.

Big end bearing wear was probably caused by the decrease in oil viscosity resulting from both oil dilution and high temperature.

IV. CONCLUSIONS

1. The addition of coal to diesel fuel in the Hatz engine decreased the brake thermal efficiency of the engine at all speeds and loads tested.

2. Addition of water (2.8 wt%) to diesel fuel in an emulsion increased brake thermal efficiency at lower loads by about 5 percent. Addition of water to the diesel fuel-coal mixture (20 wt% coal) slightly increased the brake thermal efficiency of this mixture, but not to the extent that the baseline diesel fuel efficiency was regained.

3. A mixture of diesel fuel and 20 wt% coal can save a small amount of diesel fuel (approximately 2 percent), even though the engine brake thermal efficiency is decreased.

4. A mixture of diesel fuel and 10 wt% coal shows a decrease in brake thermal efficiency great enough so that additional diesel fuel is used, to maintain the same engine speed and load as compared to the diesel fuel baseline.

5. Gaseous exhaust emissions (NO, hydrocarbons, and CO) are increased by the addition of coal to the diesel fuel, both with and without water.

6. Mass particulates in the exhaust are increased by the addition of coal to diesel fuel. This increase can be only partially accounted for by the ash content of the coal; however, the increase in exhaust particulates is only about 4 to 7 percent of the coal input.

7. Exhaust temperatures are increased by the addition of coal to the diesel fuel.

8. The evidence indicates that the coal burns late in the expansion stroke, with the time of this burning controlled by the time required to first burn the diesel fuel component, and with the rate of coal burning influenced by the oxygen content and degree of turbulent mixing in the cylinder.

9. Engine wear was abnormally high on both test engines, with high wear rates on cast iron piston rings, fuel pump plungers, and injector valves. Injector valve sticking was encountered even though valve modifications were made to reduce this occurrence.

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4. Marshall, H.P. and Walters, D.C., "An Experimental Investigation of a Coal-Slurry Fueled Engine," SAE Paper No. 770795.

5. Saxton, M.J., "Ignition and Combustion in Coal-Fired Diesel Engine: A Theoretical Model," Battelle Memorial Research Institute, 505 King Avenue, Columbus, Ohio, March 1978.

6. Tataiah, K. and Wood, C.D., "Performance of Coal-Slurry in a Diesel Engine," Final Report No. AR-1254, February 1978, Submitted to Department of Energy, Pittsburgh Energy Technology Center, 4800 Forbes Avenue, Pittsburgh, PA, 15213.

7. Ingalls, M.N., et al., "Automotive Sulfates--A CVS Compatible Sampling System," SAE Paper No. 780644.

APPENDIX A

FUEL SPECIFICATIONS

TABLE A-1. DETAILED REQUIREMENTS FOR DIESEL FUEL OILS[a,h] (Reproduced from ASTM Standards D 975)

Grade of Diesel Fuel Oil	Flash Point, °C	Cloud Point °C(°F)	Water and Sediment, vol%	Carbon Residue on 10% Residuum, %	Ash, Weight, %	Distillation Temperatures, °C(°F) 90 % Point	
	min	max	max	max	max	min	max
No. 1-D: A volatile distillate fuel oil for engines in service requiring frequent speed and load changes.	38 or legal (100)	a	0.5	0.15	0.01	---	288(550)
No. 2-D: A distillate fuel oil of lower volatility for engines in industrial and heavy mobile service.	52 or legal (125)	a	0.05	0.35	0.01	282[c](540)	338(640)
No. 4-D: A fuel oil for low and medium speed engines.	55 or legal (130)	a	0.50	---	0.01	---	---

Grade of Diesel Fuel Oil	Viscosity: Kinematic, cSt[g] at 40°C		Viscosity: Saybolt, SUS at 100°F		Sulfur[d] Wt%	Copper Strip Corrosion	Cetane Number[e]
	min	max	min	max	max	max	min
No. 1-D: A volatile distillate fuel oil for engines in service requiring frequent speed and load changes.	1.3	2.4	---	34.4	0 50 or legal	No. 3	40[f]
No. 2-D: A distillate fuel oil of lower volatility for engines in industrial and heavy mobile service.	1.9	4.1	32.6	40.1	0.50 or legal	No. 3	40[f]
No. 4-D: A fuel oil for low and medium speed engines.	5.5	24.0	45.0	125.0	2.0	---	30[f]

a = To meet special operating conditions, modifications of individual limiting requirements may be agreed upon between purchaser, seller, and manufacturer.

b = It is unrealistic to specify low-temperature properties that will insure satisfactory operation on a broad basis. Satisfactory operation should be achieved in most cases if the cloud point (or wax appearance point) is specified at 6°C above the tenth percentile minimum ambient temperature for the area in which the fuel will be used. The tenth percentile minimum ambient temperatures for the U.S. are shown in Appendix X2. This guidance is of a general nature; some equipment designs, use flow improver additives, fuel properties, and/or operations may allow higher or require lower cloud point fuels. Appropriate low temperature operability properties should be agreed upon between the fuel supplier and purchaser for the intended use and expected ambient temperatures.

c = When cloud point less than -12°C (10°F) is specified, the minimum viscosity shall be 1.7 cSt (or mm^2/s), and the 90 percent point shall be waived.

d = In countries outside the U.S.A., other sulfur limits may apply.

e = Where cetane number by Method D 613 is not available, ASTM Method D 976, Calculated Cetane Index of Distillate Fuels[2] may be used as an approximation. Where there is disagreement, method D 613 shall be the referee method.

f = Low-atmospheric temperatures, as well as engine operation at high altitudes, may require use of fuels with higher cetane ratings.

g = 1 cSt = 1 mm^2/s.

h = The values stated in SI units are to be regarded as the standard. The values in U.S. customary units are for information only.

TABLE A-2. COAL ANALYSIS AND PARTICULATE SIZE DISTRIBUTION
(Comminuted to Ultrafine Size in Union Process Company Attritor)

Coal Analysis	Wt%		
Proximate Analysis	As Received	Moisture Free	Moisture and Ash Free
Moisture	1.6	0	0
Volatile Matter	37.1	37.7	41.5
Fixed Carbon	52.2	53.1	58.5
Ash	9.1	9.2	0
	100.0	100.0	100.0
Ultimate Analysis			
Hydrogen	5.1	5.0	5.5
Carbon	74.2	75.4	83.0
Nitrogen	1.5	1.5	1.7
Oxygen	8.3	7.0	7.7
Sulfur	1.8	1.9	2.1
Ash	9.1	9.2	0
	100.0	100.0	100.0
Higher Heating Value, Btu/lb	13325	13543	14917
Lower Heating Value, Btu/lb	12853	-----	-----

Particle Size Distribution

Size, micrometers	Cumulative Frequency	Difference
0.5	100.0	0.6
0.63	99.4	2.0
0.794	97.3	5.0
1.0	92.3	9.2
1.26	83.2	14.3
1.587	68.9	17.7
2.0	51.2	18.4
2.52	32.8	13.9
3.175	18.9	10.1
4.0	8.7	5.5
5.04	3.2	2.2
6.35	1.1	0.8
8.0	0.3	0.2
10.079	0.1	0.1
12.699	0.0	0.0
16.0	0.0	0.0

Geo Mean: 2.048 micrometers
Median: 2.033 micrometers
Mode: 2.074 micrometers
Standard Dev.: 1.644 micrometers

APPENDIX B

ENGINE SPECIFICATIONS

TABLE B-1. HATZ SINGLE-CYLINDER TEST ENGINE SPECIFICATIONS

Engine:	Hatz single-cylinder, 4-stroke diesel Model E-785
Bore Diameter, mm:	85
Stroke, mm:	110
Piston Displacement, cm^3:	625
Compression Ratio:	20:1
Maximum Power (Cont.):	7.1 kW at 2500 rpm
Injection Timing:	26° BTDC
Cooling:	Air
Idle Speed, rpm:	1000

TABLE B-2. SPECIFICATIONS OF MERCEDES OM314 ENGINE

Engine:	Mercedes OM314, Type 314-910
Bore Diameter, mm:	97
Stroke, mm:	128
Number of Cylinders:	4
Piston Displacement, cm^3:	3780
Compression Ratio:	17:0
Injection Timing:	15° BTDC
Maximum Torque:	24 kW at 1800 rpm
Maximum Power at Rated Speed:	62.6 kW at 2800 rpm

APPENDIX C

HATZ ENGINE THERMAL EFFICIENCY DATA

TABLE C-1. ENGINE BRAKE THERMAL EFFICIENCIES

Fuel No.	Speed, Rpm	BMEP, kPa 150	275	400	422-525
1	1200	0.24	0.302	0.378	0.300
(2-D)	1200	0.188	0.286	0.306	0.309
	1200	0.190	0.287	0.302	0.294
	Avg	0.206	0.292	0.329	
	S	0.0295	0.009	0.043	0.043
	1800	0.217	0.299	0.332	0.322
	1800	0.199	0.269	0.307	0.314
	1800	0.200	0.267	0.293	0.308
	Avg	0.205	0.278	0.311	0.315
	S	0.010	0.018	0.020	
	2400	0.167	0.256	0.296	0.310
	2400	0.161	0.244	0.293	0.318
	2400	0.164	0.246	0.278	0.301
	Avg	0.164	0.249	0.289	0.310
	S	0.003	0.0064	0.010	
2	1200	0.230	0.292	0.305	0.301
(2-D+2.8 wt% H_2O)	1200	0.216	0.295	0.312	0.322
	1200	0.209	0.296	0.298	0.292
	Avg	0.219	0.294	0.305	0.305
	S	0.011	0.0021	0.009	
	1800	0.205	0.273	0.310	0.341
	1800	0.204	0.276	0.307	0.359
	1800	0.190	0.271	0.308	0.341
	Avg	0.200	0.273	0.308	0.347
	S	0.008	0.0025	0.0015	
	2400	0.180	0.228	0.303	0.319
	2400	0.177	0.251	0.307	0.318
	2400	0.164	0.238	0.290	0.319
	Avg	0.174	0.239	0.300	0.319
	S	0.0085	0.0115	0.0089	
3	1200	0.183	0.261	0.275	0.262
(2-D+20 wt% Coal)	1200	0.184	0.249	0.273	0.258
	1200	0.185	0.261	0.274	0.240
	Avg	0.184	0.257	0.274	0.253
	S	0.001	0.007	0.001	
	1800	0.175	0.251	0.271	0.269
	1800	0.172	0.243	0.268	0.249
	1800	0.187	0.255	0.277	0.194
	Avg	0.178	0.250	0.272	0.237
	S	0.008	0.006	0.005	

TABLE C-1. ENGINE BRAKE THERMAL EFFICIENCIES (Cont'd)

Fuel No.	Speed, rpm	BMEP, kPa 150	275	400	422-525
3	2400	0.156	0.220	0.250	0.263
(2-D+20 wt% Coal)	2400	0.151	0.209	0.256	0.208
(Cont'd)	2400	0.162	0.230	0.261	0.249
	Avg	0.156	0.220	0.256	0.240
	S	0.0055	0.011	0.006	
4	1200	0.191	0.261	0.285	0.274
(2-D+20 wt% Coal	1200	0.193	0.255	0.301	---
+2.8 wt% H_2O)	1200	0.197	0.252	0.292	0.263
	Avg	0.194	0.256	0.293	0.269
	S	0.003	0.005	0.008	
	1800	0.179	0.254	0.281	0.279
	1800	0.185	0.262	0.276	---
	1800	0.200	0.262	0.294	0.257
	Avg	0.188	0.259	0.284	0.268
	S	0.011	0.005	0.009	
	2400	0.157	0.226	0.269	0.252
	2400	0.151	0.230	---	---
	2400	0.167	0.235	0.278	0.257
	Avg	0.158	0.230	0.274	0.255
	S	0.008	0.0045	0.006	
5	1200	0.184	0.259	0.257	---
(2-D+10 wt% Coal)	1200	0.194	0.259	0.270	---
	Avg	0.189	0.259	0.264	---
	S	0.007	0	0.009	
	1800	0.187	0.250	0.279	---
	1800	0.185	0.235	0.266	---
	Avg	0.186	0.243	0.273	---
	S	0.0014	0.011	0.004	
	2400	0.144	0.219	0.242	---
	2400	0.160	0.224	0.242	---
	Avg	0.152	0.222	0.242	---
	S	0.011	0.0035	0.0	

APPENDIX D

HEAT RELEASE FROM CYLINDER PRESSURE DATA

HEAT RELEASE FROM CYLINDER PRESSURE DATA

Fuel - D-2
Speed - 1800 RPM
BMEP - 275 KPa

CRANK ANGLE DEG	CYL PR PSIA	CYL VOL CU IN	CUMU WORK IN LB	HT REL RATE B/DEG	CUMU HT RELEASE B
620	24.70	27.05	0.	0.0000	0.000
624	29:70	25.79	-.34E+02	.0070	.028
628	34.70	24.49	-.76E+02	.0057	.051
632	36.70	23.16	-.12E+03	-.0013	.046
636	47.70	21.81	-.18E+03	.0139	.101
640	54.70	20.43	-.25E+03	.0044	.119
644	59.70	19.05	-.33E+03	-.0006	.117
648	64.70	17.66	-.42E+03	-.0019	.109
652	69.70	16.27	-.51E+03	-.0032	.097
656	77.70	14.90	-.61E+03	-.0008	.093
660	84.70	13.55	-.72E+03	-.0037	.079
664	94.70	12.24	-.84E+03	-.0023	.069
668	104.70	10.96	-.97E+03	-.0043	.052
672	119.70	9.74	-.11E+04	-.0022	.043
676	134.70	8.58	-.13E+04	-.0048	.024
680	154.70	7.48	-.14E+04	-.0041	.008
684	179.70	6.46	-.16E+04	-.0042	-.009
688	214.70	5.53	-.18E+04	-.0028	-.020
692	254.70	4.69	-.20E+04	-.0047	-.039
696	314.70	3.94	-.22E+04	-.0018	-.047
700	379.70	3.30	-.24E+04	-.0049	-.066
704	459.70	2.77	-.26E+04	-.0043	-.083
708	554.70	2.36	-.28E+04	-.0031	-.096
712	644.70	2.06	-.30E+04	-.0033	-.109
716	734.70	1.87	-.31E+04	.0009	-.105
0	1014.70	1.81	-.32E+04	.0362	.039
4	1054.70	1.87	-.31E+04	.0127	.090
8	974.70	2.06	-.29E+04	.0071	.119
12	899.70	2.36	-.27E+04	.0169	.186
16	774.70	2.77	-.23E+04	.0117	.233
20	654.70	3.30	-.19E+04	.0113	.278
24	514.70	3.94	-.16E+04	-.0008	.275
28	404.70	4.69	-.12E+04	-.0016	.268
32	314.70	5.53	-.91E+03	-.0046	.250
36	254.70	6.45	-.65E+03	-.0005	.248
40	214.70	7.48	-.41E+03	.0032	.261
44	179.70	8.57	-.19E+03	.0005	.263
48	149.70	9.74	-.51E+00	-.0016	.256
52	129.70	10.96	.17E+03	.0016	.263
56	109.70	12.23	.32E+03	-.0024	.253
60	94.70	13.55	.46E+03	-.0012	.249
64	84.70	14.90	.58E+03	.0015	.255
68	69.70	16.27	.68E+03	-.0075	.224
72	59.70	17.65	.77E+03	-.0041	.208
76	54.70	19.04	.85E+03	.0011	.213
80	44.70	20.43	.92E+03	-.0086	.178

HEAT RELEASE FROM CYLINDER PRESSURE DATA

Fuel - D-2+20% w coal
Speed - 1800 RPM
BMEP - 275 KPa

CRANK ANGLE DEG	CYL PR PSIA	CYL VOL CU IN	CUMU WORK IN LB	HT REL RATE B/DEG	CUMU HT RELEASE B
620	34.70	27.05	0.	0.0000	0.000
624	36.70	25.79	-.45E+02	-.0006	-.002
628	39:70	24.49	-.94E+02	.0008	.001
632	44.70	23.16	-.15E+03	.0036	.015
636	49.70	21.81	-.21E+03	.0022	.024
640	54.70	20.43	-.29E+03	.0008	.027
644	59.70	19.05	-.37E+03	-.0006	.025
648	64.70	17.66	-.45E+03	-.0019	.018
652	69.70	16.27	-.55E+03	-.0032	.005
656	74.70	14.90	-.64E+03	-.0044	-.012
660	84.70	13.55	-.75E+03	-.0001	-.013
664	91.70	12.24	-.87E+03	-.0052	-.033
668	102.70	10.96	-.99E+03	-.0030	-.045
672	116.70	9.74	-.11E+04	-.0027	-.056
676	134.70	8.58	-.13E+04	-.0024	-.066
680	154.70	7.48	-.14E+04	-.0041	-.082
684	179.70	6.46	-.16E+04	-.0042	-.099
688	209.70	5.53	-.18E+04	-.0050	-.119
692	249.70	4.69	-.20E+04	-.0043	-.136
696	299.70	3.94	-.22E+04	-.0045	-.155
700	364.70	3.30	-.24E+04	-.0038	-.170
704	449.70	2.77	-.26E+04	-.0023	-.179
708	549.70	2.36	-.28E+04	-.0017	-.186
712	654.70	2.06	-.30E+04	-.0007	-.189
716	694.70	1.87	-.31E+04	-.0068	-.216
0	734.70	1.81	-.32E+04	.0013	-.211
4	1014.70	1.87	-.31E+04	.0476	-.020
8	1054.70	2.06	-.29E+04	.0266	.086
12	939.70	2.36	-.26E+04	.0117	.133
16	814.70	2.77	-.23E+04	.0134	.187
20	694.70	3.30	-.19E+04	.0136	.241
24	574.70	3.94	-.15E+04	.0085	.275
28	479.70	4.69	-.11E+04	.0091	.311
32	389.70	5.53	-.69E+03	.0022	.320
36	319.70	6.46	-.36E+03	.0017	.327
40	269.70	7.48	-.63E+02	.0041	.343
44	229.70	8.58	.21E+03	.0035	.357
48	189.70	9.74	.45E+03	-.0034	.344
52	159.70	10.96	.67E+03	-.0021	.335
56	134.70	12.23	.96E+03	-.0033	.322
60	114.70	13.55	.10E+04	-.0032	.309
64	98.70	14.90	.12E+04	-.0029	.297
68	84.70	16.27	.13E+04	-.0041	.281
72	71.70	17.65	.14E+04	-.0062	.256
76	64.70	19.04	.15E+04	-.0002	.255
80	54.70	20.43	.16E+04	-.0071	.227

HEAT RELEASE FROM CYLINDER PRESSURE DATA

Fuel - D-2
Speed - 1800 RPM
BMEP - 400 KPa

CRANK ANGLE DEG	CYL PR PSIA	CYL VOL CU IN	CUMU WORK IN LB	HT REL RATE B/DEG	CUMU HT RELEASE B
660	64.70	13.55	0.	0.0000	0.000
664	74.70	12.24	-.92E+02	.0006	.002
668	84.70	10.96	-.19E+03	-.0015	-.004
672	99.70	9.74	-.31E+03	.0004	-.002
676	114.70	8.58	-.43E+03	-.0023	-.011
680	134.70	7.48	-.57E+03	-.0017	-.018
684	164.70	6.46	-.72E+03	.0005	-.016
688	194.70	5.53	-.89E+03	-.0035	-.030
692	239.70	4.69	-.11E+04	-.0011	-.035
696	299.70	3.94	-.13E+04	-.0006	-.037
700	374.70	3.30	-.15E+04	-.0012	-.042
704	454.70	2.77	-.17E+04	-.0040	-.058
708	564.70	2.36	-.19E+04	-.0000	-.058
712	679.70	2.06	-.21E+04	.0004	-.057
716	774.70	1.87	-.22E+04	.0009	-.053
0	1094.70	1.81	-.23E+04	.0418	.114
4	1134.70	1.87	-.22E+04	.0133	.167
8	1094.70	2.06	-.20E+04	.0154	.229
12	1029.70	2.36	-.17E+04	.0228	.320
16	924.70	2.77	-.13E+04	.0221	.408
20	774.70	3.30	-.85E+03	.0116	.455
24	614.70	3.94	-.40E+03	.0009	.459
28	494.70	4.69	.84E+01	.0025	.469
32	394.70	5.53	.38E+03	-.0056	.446
36	304.70	6.46	.70E+03	-.0042	.429
40	249.70	7.48	.98E+03	-.0006	.427
44	204.70	8.57	.12E+04	-.0025	.417
48	164.70	9.74	.14E+04	-.0065	.391
52	134.70	10.96	.16E+04	-.0054	.369
56	109.70	12.23	.18E+04	-.0067	.342
60	89.70	13.55	.19E+04	-.0068	.315
64	74.70	14.90	.20E+04	-.0054	.294
68	64.70	16.27	.21E+04	-.0023	.284
72	59.70	17.65	.22E+04	.0024	.294
76	54.70	19.04	.23E+04	.0011	.299
80	49.70	20.43	.24E+04	-.0002	.299

HEAT RELEASE FROM CYLINDER PRESSURE DATA

Fuel - D-2+20% w coal
Speed - 1800 RPM
BMEP - 400 KPa

CRANK ANGLE DEG	CYL PR PSIA	CYL VOL CU IN	CUMU WORK IN LB	HT REL RATE B/DEG	CUMU HT RELEASE B
660	69.70	13.55	0.	0.0000	0.000
664	77.70	12.24	-.97E+02	-.0021	-.008
668	84.70	10.96	-.20E+03	-.0046	-.027
672	99.70	9.74	-.31E+03	.0004	-.025
676	114.70	8.58	-.44E+03	-.0023	-.034
680	129.70	7.48	-.57E+03	-.0047	-.053
684	149.70	6.46	-.71E+03	-.0040	-.069
688	179.70	5.53	-.87E+03	-.0020	-.077
692	214.70	4.69	-.10E+04	-.0034	-.091
696	269.70	3.94	-.12E+04	-.0002	-.091
700	354.70	3.30	-.14E+04	.0034	-.078
704	454.70	2.77	-.16E+04	.0015	-.072
708	564.70	2.36	-.18E+04	-.0000	-.072
712	639.70	2.06	-.20E+04	-.0061	-.096
716	714.70	1.87	-.21E+04	-.0013	-.101
0	1114.70	1.81	-.22E+04	.0539	.114
4	1134.70	1.87	-.21E+04	.0103	.156
8	1064.70	2.06	-.19E+04	.0103	.197
12	974.70	2.36	-.16E+04	.0169	.265
16	814.70	2.77	-.13E+04	.0070	.292
20	679.70	3.30	-.86E+03	.0095	.330
24	549.70	3.94	-.46E+03	.0042	.347
28	449.70	4.69	-.93E+02	.0051	.367
32	364.70	5.53	.25E+03	.0018	.375
36	294.70	6.46	.56E+03	-.0008	.371
40	244.70	7.48	.83E+03	.0014	.377
44	204.70	8.57	.11E+04	.0005	.379
48	169.70	9.74	.13E+04	-.0025	.369
52	139.70	10.96	.15E+04	-.0048	.350
56	114.70	12.23	.16E+04	-.0060	.325
60	94.70	13.55	.18E+04	-.0061	.301
64	79.70	14.90	.19E+04	-.0046	.283
68	64.70	16.27	.20E+04	-.0083	.250
72	54.70	17.65	.21E+04	-.0048	.230
76	44.70	19.04	.22E+04	-.0074	.200
80	39.70	20.43	.22E+04	-.0017	.194

APPENDIX E

STATISTICAL DATA AND CALCULATIONS FOR EXHAUST PARTICULATE EMISSION

TABLE E-1. PARTICULATE EMISSIONS IN G/KW-HR AT VARIOUS LOADS AND SPEEDS

Fuel No.	Speed, rpm	BMEP, kPa 150	275	400	430-525
2-D	1200	0.286 0.688	0.467	0.698 1.02	2.298*
	1800	1.904	0.842	1.077	1.753
	2400	4.109 4.06	2.581	1.614 1.335	1.791

* Obtained at 478 kPa.

Fuel No.	Speed, rpm	BMEP, kPa 150	275	400	430-525
2-D+Water	1200	0.561 0.836	0.381	0.980 0.865	1.202*
	1800	2.052	1.119	1.018	1.438
	2400	3.072 3.28	2.590	2.203 1.86	1.069

* Obtained at 463 kPa.

Fuel No.	Speed, rpm	BMEP, kPa 150	275	400	430-525
2-D+Coal	1200	4.190 4.032	3.883	3.365 3.233	3.251*
	1800	6.269	5.123	5.791	6.301**
	2400	7.144 7.308	4.563	4.223 4.982	7.362

* Obtained at 432 kPa.
** Obtained at 512 kPa.

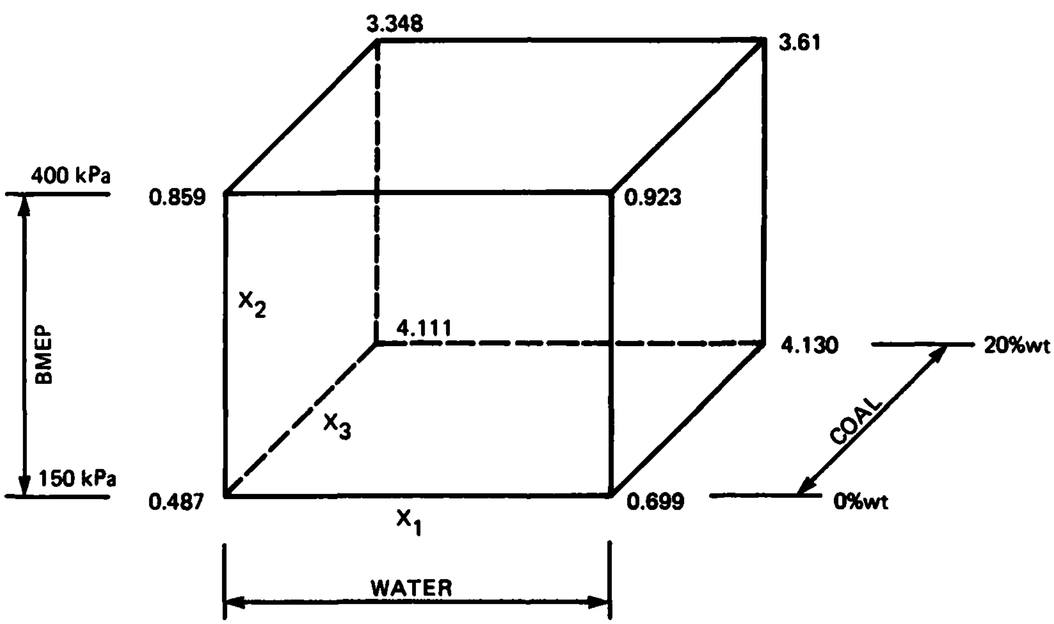
Fuel No.	Speed, rpm	BMEP, kPa 150	275	400	430-525
2-D+Coal+ Water	1200	3.905 4.360	3.687	3.409 3.861	3.409*
	1800	7.680	5.958	7.295	6.323**
	2400	9.550 9.778	5.711	4.325 5.666	4.044**

* Obtained at 442 kPa.
** Obtained at 502 kPa

FIGURE E-1. MAIN AND INTERACTION EFFECTS OF COAL, WATER, AND ENGINE LOAD ON PARTICULATE EMISSIONS

A Sample Calculation for Engine Speed of 1200 rpm

The averages of the observations are shown below at the vertices of a cube which represents 2^3 factorial.



The contrast coefficients and the variances are given in the table below:

Observation		Average	X_1	X_2	X_3	X_1X_2	X_1X_3	X_2X_3	$X_1X_2X_3$	S^2
0.286	0.688	0.487	-	-	-	+	+	+	-	0.0808
0.561	0.836	0.699	+	-	-	-	-	+	+	0.0378
0.698	1.02	0.859	-	+	-	-	+	-	+	0.01248
0.980	0.865	0.923	+	+	-	+	-	-	-	0.0066
4.19	4.032	4.11	-	-	+	+	-	-	+	0.0125
3.90	4.36	4.13	+	-	+	-	+	-	-	0.1058
3.36	3.33	3.35	-	+	+	-	-	+	-	0.0005
3.41	3.86	3.64	+	+	+	+	+	+	+	0.1012

Where X_1 denotes water

X_2 denotes load

X_3 denotes coal

S^2 denotes variance of the two observations

$$\text{The main effect of } X_1 = 1/4\ [(0.699 + 0.923 + 4.13 + 3.64) - (0.487 + 0.859 + 4.11 + 3.34)] = 0.1391$$

Similarly:

Main effect of $X_2 = -0.171$

$X_3 = 3.058$

$X_1X_2 = 0.0242$

$X_1X_3 = 0.001$

$X_2X_3 = 0.469$

$X_1X_2X_3 = 0.096$

Assuming that the observations were obtained at random order, one can estimate the pooled variance from the above individual variances as:

S^2 pooled = $(0.0808 + 0.0378 + 0.01248 + \ldots + 0.10125)/8 = 0.3577/8 = 0.0447$

APPENDIX F

EXHAUST SULFATE EMISSION DATA

TABLE F-1. SULFATE EMISSIONS IN MG/KW-HR AT VARIOUS LOADS AND SPEEDS

Fuel No.	Speed, rpm	BMEP, kPa 150	275	400	525
1	1200	25.77 20.28	7.64	7.58 14.39	21.48*
	1800	44.77	13.627	16.00	18.06
	2400	54.907 33.69	39.12	35.11 27.37	30.27
	* Obtained at 478 kPa.				
2	1200	24.92 23.55	10.73	19.50 44.51	11.62
	1800	35.34	20.77	14.95	17.78
	2400	41.81 40.94	36.08	38.41 35.06	29.12
	* Obtained at 463 kPa.				
3	1200	253.566 193.735	144.039	76.048 82.351 80.282	43.705*
	1800	228.145	147.946	123.821	59.772**
	2400	193.908 167.118	125.307	72.866 82.102	66.464
	* Obtained at 432 kPa. ** Obtained at 512 kPa.				
4	1200	245.09 231.217	142.100	77.220 82.103	48.089*
	1800	218.667	136.185	112.409	63.446**
	2400	270.296 199.751	121.494	78.223 82.065	58.190**
	* Obtained at 442 kPa. ** Obtained at 502 kPa.				

APPENDIX G

HATZ ENGINE COMPONENT WEAR MEASUREMENTS AND PHOTOGRAPHS

TABLE G-1. HATZ DIESEL E-385 RING WEAR

Rings*	Before, in.(mm)	After, in.(mm)	Wear, in.(mm)	Material
1	0.0972(2.469)	0.0962(2.443)	0.0010(0.025)	Chrome
2	0.0971(2.466)	0.0976(2.479)	0.0005(0.013)	Cast Iron
3	0.1563(3.970)	0.1569(3.985)	0.0006(0.015)	Cast Iron
4	0.1560(3.962)	0.1568(3.983)	0.0004(0.010)	Cast Iron

* Measurement is an average of two point 180° apart.

TABLE G-2. HATZ DIESEL E-385 RING GAP MEASUREMENT

Rings*	Before, in.(mm)	After, in.(mm)	Wear, in.(mm)	Material
1	0.016(0.406)	0.030(0.762)	0.014(0.356)	Chrome
2	0.018(0.457)	0.177(4.496)	0.157(3.988)	Cast Iron
3	0.018(0.457)	0.301(7.645)	0.283(7.188)	Cast Iron
4	0.020(0.508)	0.179(4.547)	0.159(4.039)	Cast Iron

* Measurement taken 5/8 in. from bottom of bore.

TABLE G-3. HATZ DIESEL E-385 RING GROOVE WIDTH MEASUREMENT

Groove*	Before, in.(mm)	After, in.(mm)	Wear, in.(mm)
1	0.100(2.54)	0.1112(2.82)	0.0112(0.28)
2	0.100(2.54)	0.1026(2.61)	0.0026(0.07)
3	0.158(4.01)	0.1589(4.04)	0.0006(0.015)
4	0.158(4.01)	0.1606(4.08)	0.0006(0.015)

TABLE G-4. HATZ DIESEL E-385 CYLINDER BORE MEASUREMENTS

Location	Bore Diameter, in.(mm)		
Long.*	Before	After	Wear, in.(mm)
Top	3.3464(84.998)	3.3503(85.098)	0.0039(0.099)
Middle	3.3465(85.001)	3.3480(85.039)	0.0015(0.038)
Bottom	3.3474(85.024)	3.3524(85.151)	0.0150(0.381)
Trans.*			
Top	3.3475(85.026)	3.3518(85.136)	0.0043(0.109)
Middle	3.3478(85.034)	3.3490(85.065)	0.0012(0.030)
Bottom	3.3474(85.024)	3.3524(85.151)	0.0050(0.127)

* Measurements taken at three points.

TABLE G-5. HATZ DIESEL E-385 PISTON DIAMETER MEASUREMENT

	Diameter, in.(mm)		
Location*	Before	After	Wear
Top	3.3426(84.902)	3.3363(84.742)	0.0063(0.160)
Bottom	3.3442(84.943)	3.3428(84.907)	0.0014(0.036)

* Measurements taken on thrust side of piston.

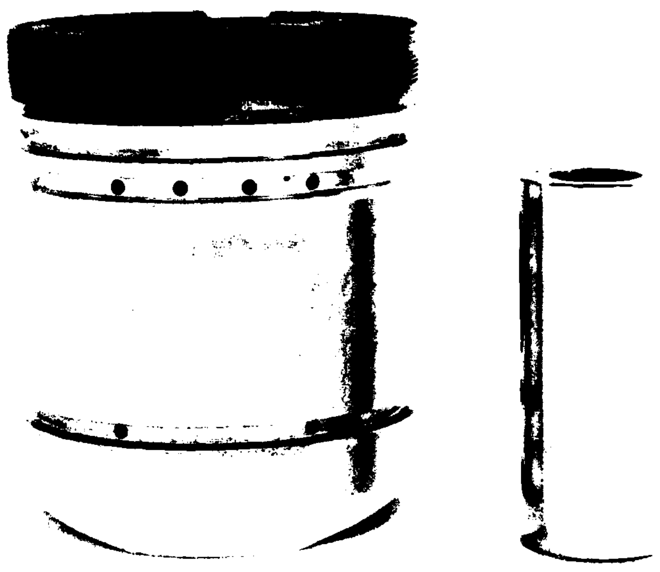


FIGURE G-1 FRONT VIEW OF HATZ PISTON AND PIN BEFORE PERFORMANCE TEST

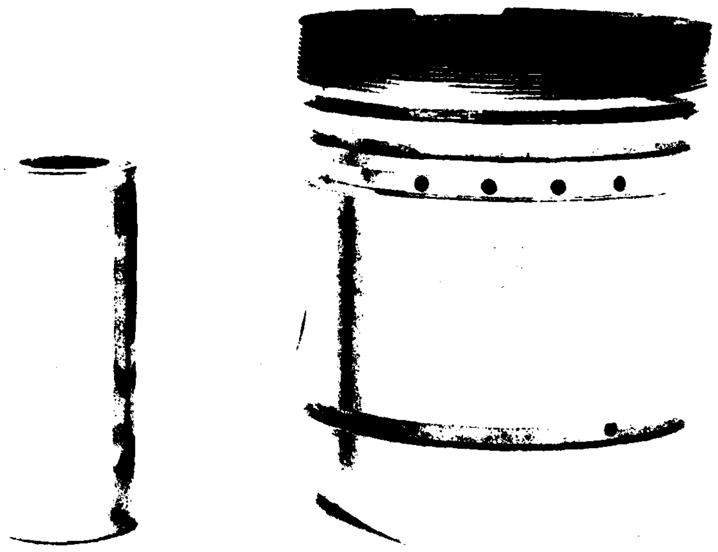


FIGURE G-2 REAR VIEW OF HATZ PISTON AND PIN BEFORE PERFORMANCE TEST

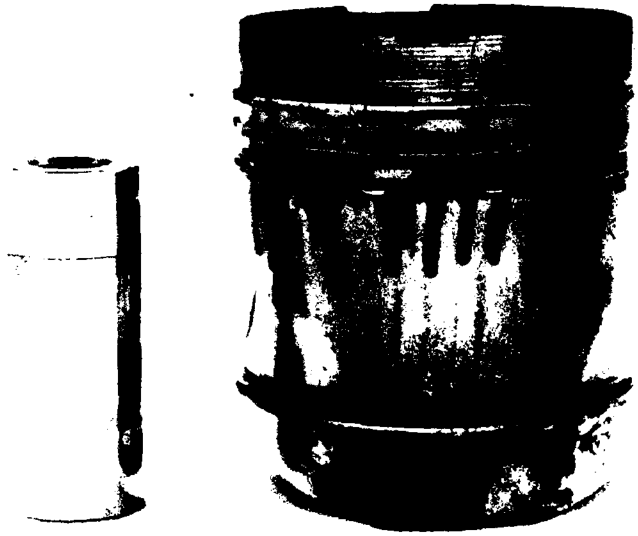


FIGURE G-3 FRONT VIEW OF HATZ PISTON AND PIN AFTER PERFORMANCE TEST

FIGURE G-4 REAR VIEW OF HATZ PISTON AND PIN AFTER PERFORMANCE TEST

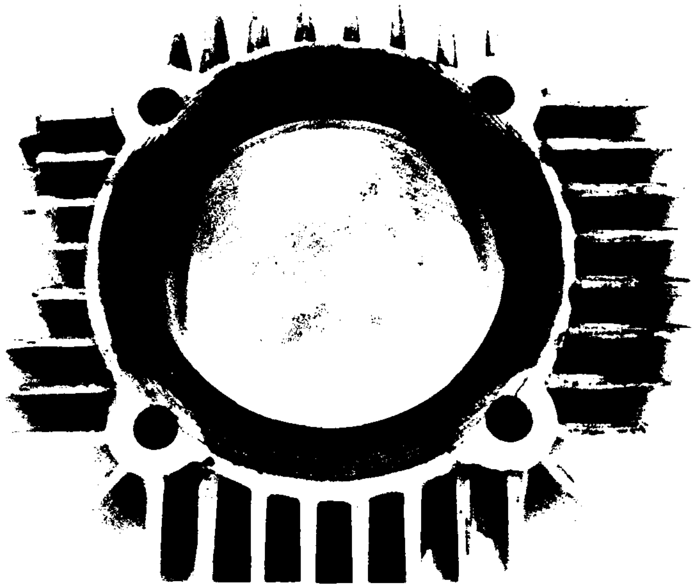


FIGURE G-5 HATZ CYLINDER BEFORE PERFORMANCE TEST, VIEW 1

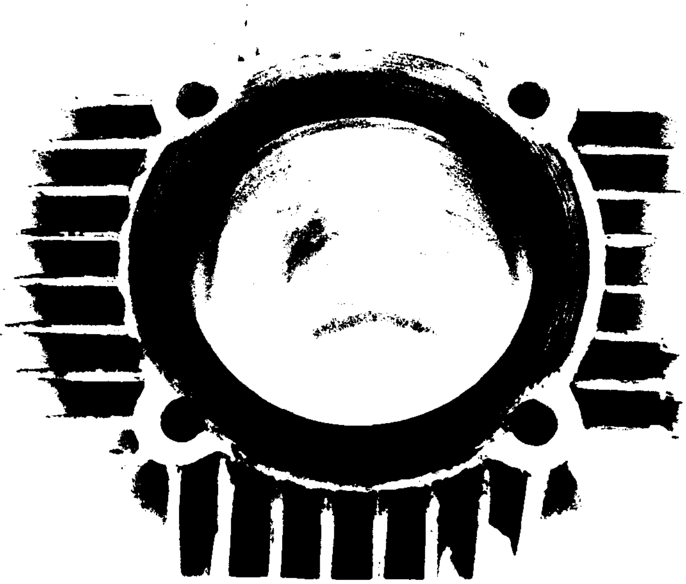


FIGURE G-6 HATZ CYLINDER BEFORE PERFORMANCE TEST, 180° FROM VIEW 1

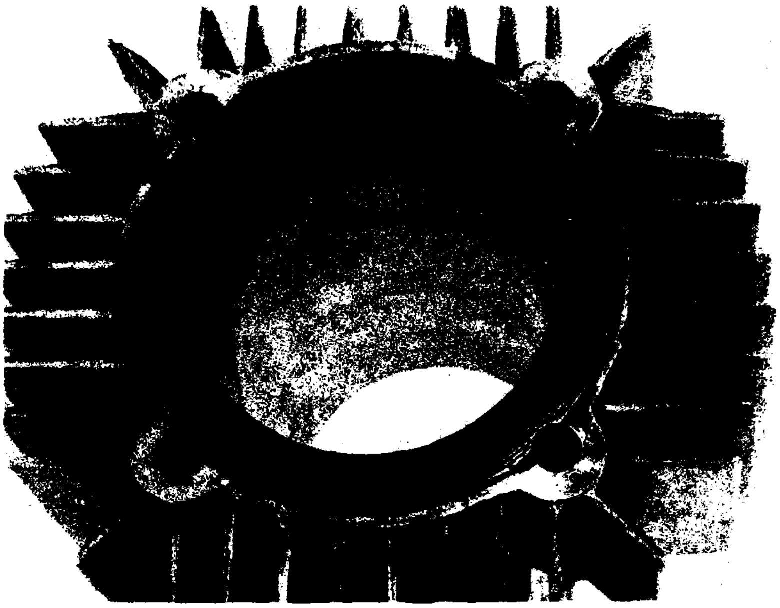


FIGURE G-7 HATZ CYLINDER AFTER PERFORMANCE TEST

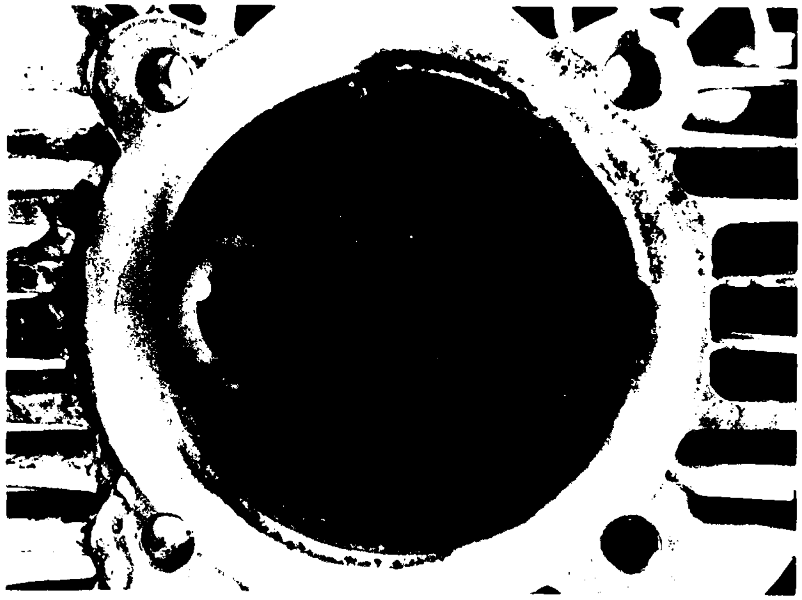


FIGURE G-8 HATZ HEAD SHOWING THE VALVES AND INJECTION CHAMBER BEFORE THE PERFORMANCE TEST

FIGURE G-9 HATZ HEAD SHOWING THE VALVES AND INJECTION CHAMBER AFTER THE PERFORMANCE TEST

FIGURE G-10 HATZ INTAKE AND EXHAUST VALVES BEFORE THE PERFORMANCE TEST, VIEW 1

FIGURE G-11 HATZ INTAKE AND EXHAUST VALVES BEFORE THE PERFORMANCE TEST, 180° FROM VIEW 1

FIGURE G-12 HATZ INTAKE AND EXHAUST VALVES AFTER THE PERFORMANCE TEST, VIEW 1

FIGURE G-13 HATZ INTAKE AND EXHAUST VALVES AFTER THE PERFORMANCE TEST, 180° FROM VIEW 1

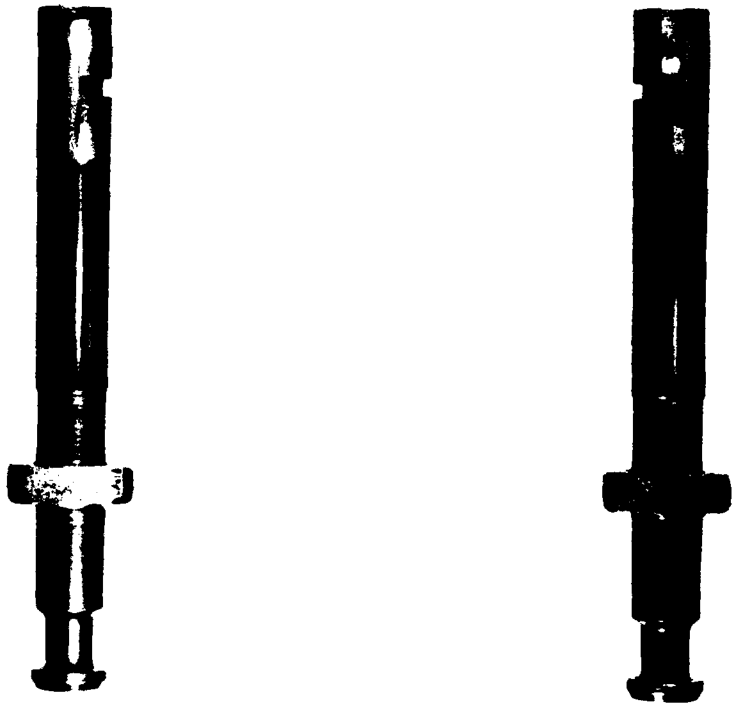


FIGURE G-14 TWO VIEWS OF HATZ FUEL PUMP PLUNGER

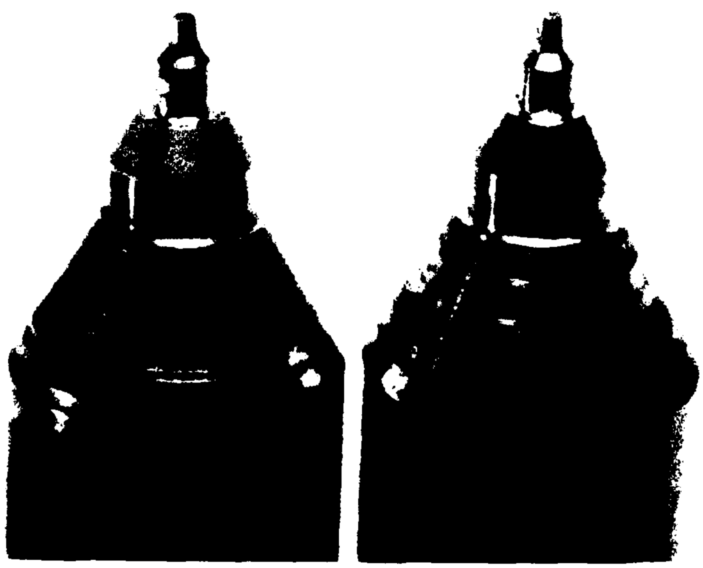


FIGURE G-15 NEW AND USED INJECTOR NOZZLE VALVES

APPENDIX H

MERCEDES ENGINE WEAR MEASUREMENTS

TABLE H-1. PISTON WEAR

Engine: Mercedes, OM314
Fuel: MICO fuel with 20 wt% Coal
Speed: 2400 rpm
Load: 51.5 psi BMEP

Piston No.	Location	Diameter, in.(mm) Before	After	Wear, in.(mm) (Difference)
1	Top	3.7993(96.502)	3.7942(96.373)	0.005(0.127)
	Middle	3.8089(96.746)	3.8071(96.700)	0.002(0.051)
	Bottom	3.8134(96.860)	3.8129(96.848)	0.001(0.025)
2	Top	3.8012(96.550)	3.7957(96.411)	0.006(0.152)
	Middle	3.8098(96.769)	3.8084(96.733)	0.001(0.025)
	Bottom	3.8130(96.850)	3.8121(96.821)	0.001(0.025)
3	Top	3.8008(96.540)	3.7989(96.492)	0.002(0.051)
	Middle	3.8095(96.761)	3.8082(96.728)	0.001(0.025)
	Bottom	3.8132(96.855)	3.8128(96.845)	0.0004(0.010)
4	Top	3.8004(96.530)	3.7968(96.439)	0.004(0.102)
	Middle	3.8093(96.756)	3.8070(96.698)	0.002(0.051)
	Bottom	3.8129(96.848)	3.8128(95.845)	0.001(0.025)

TABLE H-2. WRIST PIN WEAR

Engine: Mercedes, OM314
Fuel: MICO fuel with 20 wt% Coal
Speed: 2400 rpm

Piston No.	Location	Diameter, in.(mm) Before	After	Wear, in.(mm) (Difference)
1	End	1.4170(35.99)	1.4170(35.99)	0.0(0.000)
	Middle	1.4170(35.99)	1.4170(35.99)	0.0(0.000)
2	End	1.4170(35.99)	1.4170(35.99)	0.0(0.000)
	Middle	1.4170(35.99)	1.4170(35.99)	0.0(0.000)
3	End	1.4171(35.99)	1.4171(35.99)	0.0(0.000)
	Middle	1.4171(35.99)	1.4170(35.99)	0.0001(0.003)
4	End	1.4171(35.99)	1.4171(35.99)	0.0(0.000)
	Middle	1.4171(35.99)	1.4171(35.99)	0.0(0.000)

TABLE H-3. WRIST PIN BUSHING WEAR

Engine: Mercedes, OM314
Fuel: MICO fuel with 20 wt% Coal
Speed: 2400 rpm
Load: 51.5 psi BMEP

Bushing No.	Location	Bore Diameter, in.(mm) Before	After	Wear, in.(mm) (Difference)
1	Vert	1.4184(36.027)	1.4199(36.065)	0.0015(0.0381)
	Horz	1.4183(36.025)	1.4181(36.020)	0.0002(0.0051)
2	Vert	1.4189(36.040)	1.4203(36.076)	0.0014(0.0356)
	Horz	1.4182(36.022)	1.4184(36.027)	0.0002(0.0051)
3	Vert	1.4187(36.035)	1.4196(36.058)	0.0009(0.0229)
	Horz	1.4183(36.025)	1.4184(36.027)	0.0001(0.0025)
4	Vert	1.4189(36.040)	1.4195(36.055)	0.0006(0.0152)
	Horz	1.4183(36.025)	1.4182(36.022)	0.0001(0.0051)

TABLE H-4. RING THICKNESS WEAR

Engine: Mercedes, OM314
Fuel: MICO fuel with 20 wt% Coal
Speed: 2400 rpm
Load: 51.5 psi BMEP

Cylinder No.	Ring No.	Avg Thickness, In.(cm) Before	After	Wear, in.(cm) (Difference)	Ring Material
1	1	0.1155(2.934)	0.1153(2.929)	0.0002(0.005)	Chrome
	2	0.1172(2.977)	0.1167(2.964)	0.0005(0.013)	Cast Iron
	3	0.1173(2.979)	0.1168(2.967)	0.0005(0.013)	Cast Iron
	4	0.2158(5.481)	0.2158(5.481)	0.0000(0.000)	Chrome
	5	0.2160(5.486)	0.2160(5.486)	0.0000(0.000)	Cast Iron
2	1	0.1150(2.921)	0.1149(2.918)	0.0001(0.003)	Chrome
	2	0.1173(2.979)	0.1168(2.967)	0.0005(0.013)	Cast Iron
	3	0.1171(2.974)	0.1168(2.967)	0.0003(0.008)	Cast Iron
	4	0.2160(5.486)	0.2158(5.481)	0.0002(0.005)	Chrome
	5	0.2158(5.481)	0.2157(5.479)	0.0001(0.003)	Cast Iron
3	1	0.1155(2.934)	0.1153(2.929)	0.0002(0.005)	Chrome
	2	0.1172(2.977)	0.1168(2.967)	0.0004(0.102)	Cast Iron
	3	0.1173(2.979)	0.1170(2.972)	0.0003(0.008)	Cast Iron
	4	0.2160(5.486)	0.2159(5.484)	0.0001(0.003)	Chrome
	5	0.2158(5.481)	0.2157(5.479)	0.0001(0.003)	Cast Iron
4	1	0.1150(2.921)	0.1148(2.916)	0.0002(0.005)	Chrome
	2	0.1172(2.977)	0.1167(2.964)	0.0005(0.033)	Cast Iron
	3	0.1176(2.987)	0.1170(2.972)	0.0006(0.015)	Cast Iron
	4	0.2159(5.484)	0.2158(5.481)	0.0001(0.003)	Chrome
	5	0.2158(5.481)	0.2155(5.474)	0.0003(0.008)	Cast Iron

TABLE H-5. RING GROOVE WEAR

Engine: Mercedes, OM314
Fuel: MICO fuel with 20 wt% Coal
Speed: 2400 rpm
Load: 51.5 psi BMEP

Cylinder No.	Groove No.	Groove Width, In.(cm) Before	After	Wear, in.(cm) (Difference)
1	1	0.003(0.076)	0.010(0.254)	0.007(0.178)
	2	0.003(0.076)	0.005(0.127)	0.002(0.051)
	3	0.003(0.076)	0.004(0.102)	0.001(0.254)
	4	0.0015(0.0381)	0.002(0.051)	0.0005(0.013)
	5	0.001(0.025)	0.0015(0.0381)	0.0005(0.013)
2	1	0.003(0.076)	0.009(0.229)	0.006(0.152)
	2	0.003(0.076)	0.005(0.127)	0.002(0.051)
	3	0.003(0.076)	0.004(0.102)	0.001(0.025)
	4	0.0015(0.0381)	0.0015(0.0381)	0.000(0.000)
	5	0.0015(0.0381)	0.0015(0.0381)	0.000(0.000)
3	1	0.003(0.076)	0.011(0.279)	0.008(0.203)
	2	0.003(0.076)	0.005(0.127)	0.002(0.051)
	3	0.003(0.076)	0.004(0.102)	0.001(0.025)
	4	0.0015(0.0381)	0.002(0.051)	0.0005(0.013)
	5	0.001(0.025)	0.0015(0.0381)	0.0005(0.013)
4	1	0.003(0.076)	0.010(0.254)	0.007(0.178)
	2	0.003(0.076)	0.005(0.127)	0.002(0.051)
	3	0.003(0.076)	0.004(0.102)	0.001(0.0254)
	4	0.0015(0.0381)	0.002(0.051)	0.0005(0.013)
	5	0.0015(0.0381)	0.002(0.051)	0.0005(0.013)

TABLE H-6. RING WEAR BY GAP MEASUREMENT

Engine: Mercedes, OM314
Fuel: MICO fuel with 20 wt% coal
Speed: 2400 rpm
Load: 51.5 psi BMEP

Cylinder No.	Ring No.	Gap, in.(cm) Before	After	Wear, in.(cm) (Difference)
1	1	0.026(0.660)	0.041(1.041)	0.015(0.381)
	2	0.026(0.660)	0.176(4.470)	0.150(3.810)
	3	0.026(0.660)	0.154(3.912)	0.128(3.251)
	4	0.021(0.533)	0.045(1.143)	0.024(0.610)
	5	0.021(0.533)	0.126(3.200)	0.105(2.667)
2	1	0.023(0.584)	0.038(0.965)	0.015(0.381)
	2	0.023(0.584)	0.150(3.810)	0.127(3.226)
	3	0.021(0.533)	0.138(3.505)	0.117(2.972)
	4	0.020(0.508)	0.044(1.118)	0.024(0.610)
	5	0.020(0.508)	0.130(3.302)	0.110(2.794)
3	1	0.022(0.559)	0.038(0.965)	0.016(0.406)
	2	0.024(0.569)	0.156(3.962)	0.132(3.353)
	3	0.024(0.569)	0.144(3.658)	0.120(3.048)
	4	0.020(0.508)	0.045(1.143)	0.025(0.635)
	5	0.020(0.508)	0.128(3.251)	0.108(2.743)
4	1	0.018(0.457)	0.042(1.067)	0.024(0.610)
	2	0.018(0.457)	0.187(4.750)	0.169(4.293)
	3	0.028(0.711)	0.156(3.962)	0.128(3.251)
	4	0.024(0.569)	0.045(1.143)	0.021(0.533)
	5	0.023(0.584)	0.156(3.962)	0.133(3.378)

TABLE H-7. CYLINDER BORE WEAR

Engine: Mercedes, OM314
Fuel: *MICO fuel with 20 wt% coal*
Speed: 2400 rpm
Load: 51.5 psi BMEP

Cylinder No.	Location Horz	Location Vert	Bore Diameter, in.(cm) Before	Bore Diameter, in.(cm) After	Wear, in.(cm) (Difference)
1	Long	Top	3.8213(97.061)	3.8254(97.165)	0.004(0.102)
		Middle	3.8212(97.058)	3.8246(97.145)	0.003(0.076)
		Bottom	3.8210(97.053)	3.8221(97.081)	0.001(0.025)
	Trans	Top	3.8218(97.074)	3.8264(97.191)	0.005(0.127)
		Middle	3.8216(97.069)	3.8255(97.168)	0.004(0.102)
		Bottom	3.8210(97.053)	3.8221(97.081)	0.001(0.025)
2	Long	Top	3.8211(97.056)	3.8237(97.122)	0.003(0.076)
		Middle	3.8210(97.053)	3.8231(97.107)	0.002(0.051)
		Bottom	3.8203(97.036)	3.8217(97.071)	0.001(0.025)
	Trans	Top	3.8207(97.046)	3.8253(97.163)	0.005(0.127)
		Middle	3.8210(97.053)	3.8237(97.122)	0.003(0.076)
		Bottom	3.8197(97.020)	3.8209(97.050)	0.001(0.025)
3	Long	Top	3.8212(97.058)	3.8246(97.145)	0.003(0.076)
		Middle	3.8210(97.053)	3.8234(97.114)	0.002(0.051)
		Bottom	3.8205(97.041)	3.8211(97.056)	0.001(0.025)
	Trans	Top	3.8214(97.064)	3.8267(97.198)	0.005(0.127)
		Middle	3.8216(97.069)	3.8242(97.135)	0.003(0.076)
		Bottom	3.8206(97.043)	3.8208(97.048)	0.0002(0.005)
4	Long	Top	3.8212(97.058)	3.8255(97.168)	0.004(0.102)
		Middle	3.8210(97.033)	3.8241(97.132)	0.003(0.076)
		Bottom	3.8203(97.036)	3.8211(97.056)	0.0008(0.025)
	Trans	Top	3.8213(97.061)	3.8215(97.066)	0.0002(0.005)
		Middle	3.8217(97.071)	3.8249(97.152)	0.003(0.076)
		Bottom	3.8208(97.048)	3.8213(97.061)	0.0005(0.013)

TABLE H-8. MAIN BEARING WEAR

Engine: Mercedes, OM314
Fuel: MICO fuel with 20 wt% Coal
Speed: 2400 rpm
Load: 51.5 psi BMEP

Bearing No.	Location	Bore Diameter, in.(cm) Before	After	Wear, in.(cm) (Difference)
1	Horz.	3.4645(87.998)	3.4645(87.998)	0.000(0.000)
	Vert.	3.4645(87.998)	3.4643(87.993)	0.0002(0.005)
2	Horz.	3.4645(87.998)	3.4644(87.996)	0.0001(0.003)
	Vert.	3.4645(87.998)	3.4643(87.993)	0.0002(0.005)
3	Horz.	3.4645(87.998)	3.4644(87.996)	0.0001(0.003)
	Vert.	3.4645(87.998)	3.4643(87.993)	0.0002(0.005)
4	Horz.	3.4645(87.998)	3.4642(87.991)	0.0003(0.008)
	Vert.	3.4645(87.998)	3.4643(87.993)	0.0002(0.005)
5	Horz.	3.4645(87.998)	3.4641(87.988)	0.0004(0.010)
	Vert.	3.4645(87.998)	3.4639(87.983)	0.0006(0.015)

Bearing No.	Clearance, in.(cm) Before	After	Wear, in.(cm) (Difference)
1	0.0055(0.140)	0.0075(0.191)	0.002(0.051)
2	0.005(0.127)*	0.006(0.152)**	0.001(0.025)
3	0.005(0.127)	0.007(0.178)	0.002(0.025)
4	0.005(0.127)	0.006(0.152)	0.001(0.025)
5	0.005(0.127)	0.009(0.229)	0.004(0.102)

* Note: Thrust Bearing Clearance 0.006(0.152)
** Note: Thrust Bearing Clearance 0.013(0.330) 0.007(0.178)

TABLE H-9. CONNECTING ROD JOURNAL WEAR

Engine: Mercedes, OM314
Fuel: MICO fuel with 20 wt% Coal
Speed: 2400 rpm
Load: 51.5 psi BMEP

Cylinder No.	Location	Journal, Dia., in.(mm) Before	After	Wear, in.(cm) (Differnece)
1	Horz	2.3620(59.995)	2.3620(59.995)	0.000(0.000)
	Vert	2.3620(59.995)	2.3611(59.972)	0.0009(0.023)
2	Horz	2.3620(59.995)	2.3620(59.995)	0.000(0.000)
	Vert	2.3620(59.995)	2.6313(66.835)	0.0007(0.0178)
3	Horz	2.3620(59.995)	2.3620(59.995)	0.000(0.000)
	Vert	2.3620(59.995)	2.3603(59.952)	0.0017(0.043)
4	Horz	2.3620(59.995)	2.3619(59.992)	0.0001(0.003)
	Vert	2.3620(59.995)	2.3611(59.972)	0.0009(0.023)

Cylinder No.	Clearance, in.(cm) Before	After	Wear, in.(cm) (Difference)
1	0.0035(0.089)	0.007(0.178)	0.0035(0.089)
2	0.003(0.076)	0.005(0.127)	0.002(0.051)
3	0.0035(0.089)	0.007(0.178)	0.0035(0.089)
4	0.003(0.076)	0.007(0.178)	0.004(0.102)

TABLE H-10. VALVE LIFTER WEAR

Engine: Mercedes, OM314
Fuel: MICO fuel with 20 wt% Coal
Speed: 2400 rpm
Load: 51.5 psi BMEP

Cylinder No.	Lifter No.	Location	Measurement, in.(cm) Before	After	Wear, in.(cm) (Difference)
1	1	length	2.3670(60.122)	2.3667(60.114)	0.0003(0.008)
		dia	1.1013(27.973)	1.1013(27.973)	0.000(0.000)
	2	length	2.3670(60.122)	2.3668(60.167)	0.0002(0.005)
		dia	1.1013(27.973)	1.1012(27.970)	0.0001(0.003)
2	3	length	2.3669(60.119)	2.3667(60.114)	0.0002(0.005)
		dia	1.1013(27.973)	1.1012(27.970)	0.0001(0.003)
	4	length	2.3671(60.124)	2.3668(60.117)	0.0002(0.005)
		dia	1.1013(27.973)	1.1013(27.973)	0.000(0.000)
3	5	length	2.3674(60.132)	2.3672(60.127)	0.0002(0.005)
		dia	1.1018(27.986)	1.1014(27.976)	0.0004(0.010)
	6	length	2.3671(60.124)	2.3669(60.119)	0.0002(0.005)
		dia	1.1015(27.978)	1.1012(27.970)	0.0003(0.008)
4	7	length	2.3672(60.127)	2.3669(60.119)	0.0003(0.008)
		dia	1.1015(27.978)	1.1014(27.975)	0.0001(0.003)
	8	length	2.3674(60.132)	2.3671(60.124)	0.0003(0.008)
		dia	1.1015(27.978)	1.1013(27.973)	0.0002(0.005)

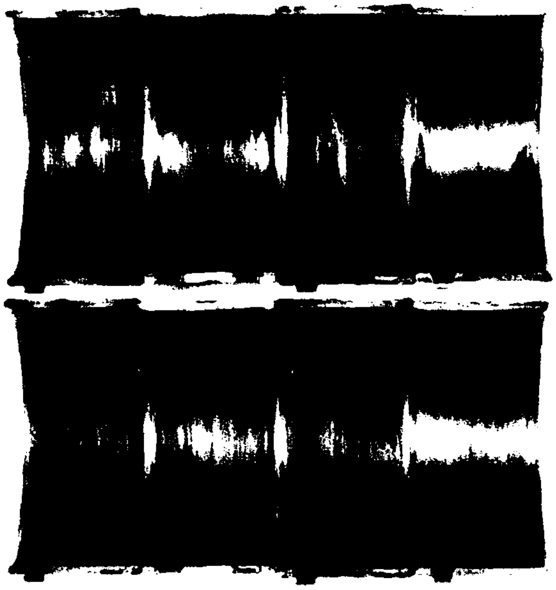


FIGURE H-1. MERCEDES ROD BEARING SHELLS TAKEN AFTER THE ENDURANCE TEST

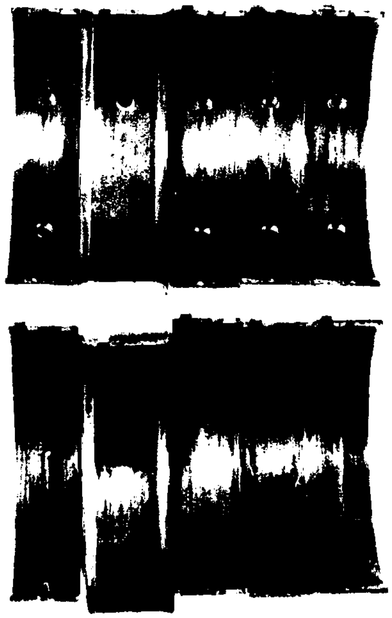


FIGURE H-2. MERCEDES MAIN BEARING SHELLS TAKEN AFTER THE ENDURANCE TEST

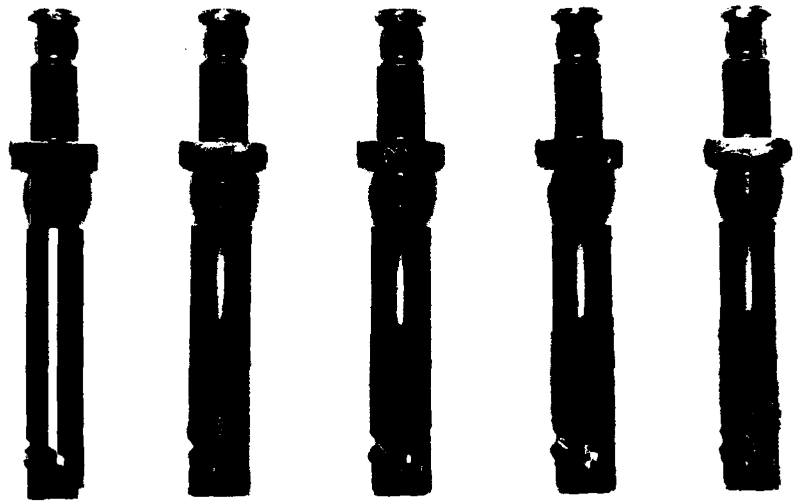


FIGURE H-3 MERCEDES NEW AND USED PUMP PLUNGERS, VIEW 1

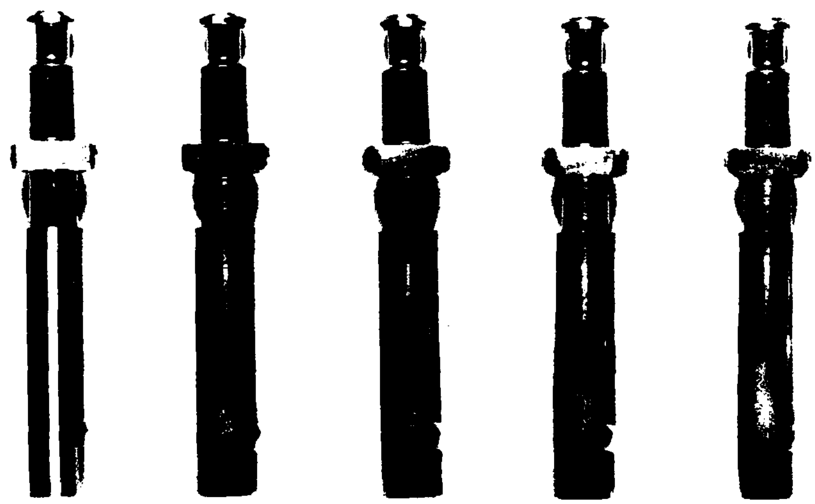


FIGURE H-4 MERCEDES NEW AND USED PUMP PLUNGERS, 180° FROM VIEW 1

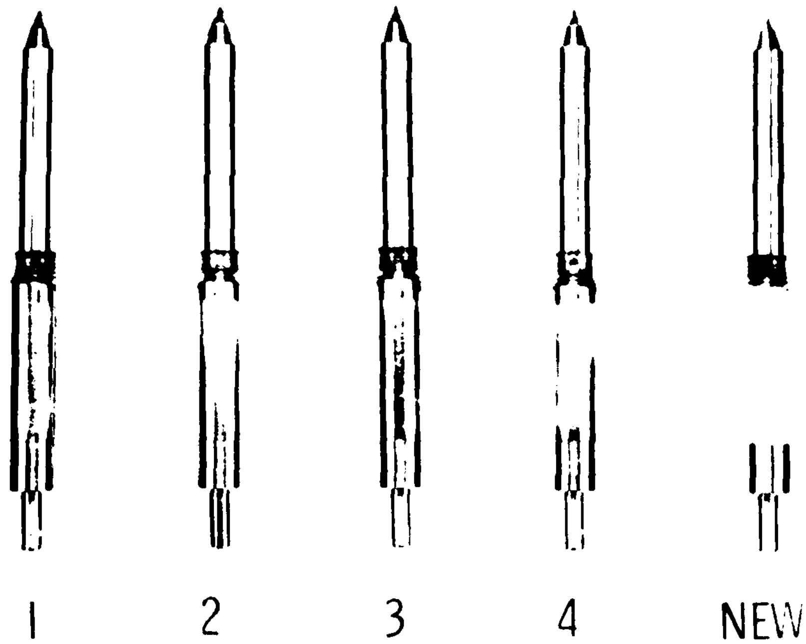


FIGURE H-5. MERCEDES INJECTOR NEEDLE VALVES

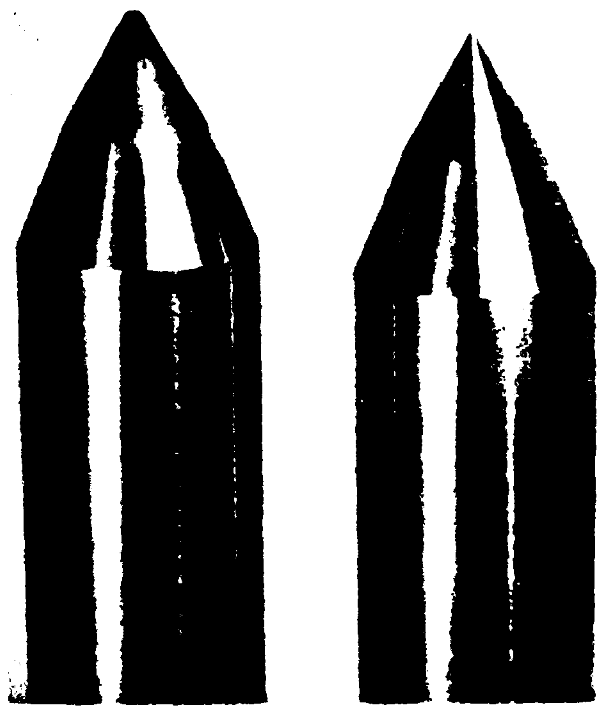


FIGURE H-6. USED AND NEW INJECTOR NEEDLE VALVE TIPS

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DRCQA-E (MR SMART) 1
DRCDE-DG 1
DRCRE-TF 2
5001 EISENHOWER AVE
ALEXANDRIA VA 22333

CDR
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DRDTA-NS (DR PETRICK) 1
DRDTA-J 1
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CDR
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OFC OF PROJ MGR, XM-1 TANK SYS
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PROG MGR, FIGHTING VEHICLE SYS
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